REMOTELY SENSED CROP TEMPERATURE FOR WATER RESOURCES MANAGEMENT

Project Completion Report for the Period
October 1, 1977 - September 30, 1980

To the Office of Water Research and Technology
U.S. Department of the Interior

Nebraska Water Resources Research Institute
Project B-044-NEB, Agreement No. 14-34-0001-8097

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Agricultural Meteorology Progress Report 80-5

Center for Agricultural Meteorology and Climatology
Institute of Agriculture and Natural Resources
University of Nebraska-Lincoln

November, 1980

The work upon which this publication is based was supported in part by funds provided by the Office of Water Research and Technology, B-044-NEB, U.S. Dept. of the Interior, Washington, D.C., as authorized by the Water Research and Development Act of 1978.

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ABSTRACT

The overall goal of our research was to evaluate the use of crop temperature data as a tool in the management of water resources. The specific objectives of our studies were (1) to determine the crop temperature response of some major agronomic crops to various levels of water stress; (2) to test methods based on crop temperature or other remotely sensed data to estimate crop water stress conditions and to evaluate the utility of these methods for their ability to estimate crop yields, severity of water stress and crop phenological development, and (3) to determine the feasibility of using crop temperature as a guide for irrigation scheduling.

Crop temperatures were measured with an infrared thermometer, with attached leaf thermocouples and with airborne multispectral scanners. Corn and sorghum were the principal crops studied. Some data were also obtained for soybeans and alfalfa. Studies were conducted at the University of Nebraska Sandhills Agricultural Laboratory and at the University of Nebraska Mead Field Laboratory.

The primary findings of our research are summarized as follows:

1. After about 75% plant cover was achieved, the temperature of well-watered crops measured with an infrared thermometer (T_{ir}) agreed to within about 1 C of the temperature measured with attached leaf thermocouples (T_{TC}). For crops under water stress the agreement was found to be within about 2.5 C.

2. Different species of crops growing under similar climatic conditions and water regimes may have different canopy temperatures. This difference in canopy temperature relates to the crop water use for, in general, the cooler the crop the greater the transpiration and, hence, the water use rate.

3. Under fully irrigated conditions T_{ir} values were not affected by plant population but under water stress conditions T_{ir} was consistently 1-2 C warmer in plots with high plant populations than in plots with low plant populations.

4. Crop temperatures obtained at midday with an IR thermometer when the observed faced north and viewed leaves on the south sides of plants were similar to those obtained when the observed faced south under well-watered conditions. Under water stress conditions crop temperatures obtained when facing north were about 1-2 C warmer than those obtained when facing south.

5. Crop temperature at midday was found to be a function of the level of water stress. Water stressed plants were often 5 to 7 C warmer than nonstressed plants and differences as great as 12.8 C were observed. At night differences in crop temperature of stressed and non-stressed vegetation were negligible.

6. The optimum time to measure the maximum temperature difference between stressed and nonstressed crops was found, generally, between 1300 and 1500 hrs solar time. A good time to make crop temperature readings for water stress evaluation is about 1400 hrs.

7. Summation of the midday crop temperature differences (TSD) between water stressed and nonstressed corn during the pollination and grain filling periods was directly related to

decreases in final grain yield. In sorghum the grain yield reductions were directly related to TSD values accumulated over the entire growing season.

8. Similar percentage reduction in grain yields as a function of accumulated TSD values were observed for 9 hybrids of corn and 2 hybrids of sorghum.

9. With light to moderate water stress the canopy temperature of corn was often below air temperature at mid-day. Severely stressed plants, however, were several degrees warmer than air.

10. The time of day at which temperature difference between well-watered and stressed vegetation develops indicated the severity of stress. If the temperature difference appears by mid-morning the level of water stress was moderate to severe. If the difference did not become evident until mid-afternoon the stress was mild to moderate. A procedure for calculating a stress severity index based upon crop temperature measurements during the morning and afternoon was developed and evaluated.

11. The standard deviation of mid-day canopy temperature in plots of well watered corn and sorghum was about 0.3 C. Values exceeding 0.3 C indicate that some plants in a plot are experiencing water stress and the need for irrigation is indicated. Standard deviations of crop temperature under water stress conditions was found to be as great as 4.2 C.

12. Irrigations were scheduled in corn using crop temperature data. Grain yields from a plot in which irrigations were initiated when the range in crop temperatures across a plot reached 0.8 C (0.8 CTV) were not significantly different from the yields of a fully-irrigated plot. Only 120 mm of water was

applied to the 0.8 CTV plot as compared to 260 mm of water on the fully irrigated plot. Other irrigations were initiated when average plot temperatures became 1.0 or 3.0 C warmer than the well-watered plot. Yield was reduced most in the 3.0 C plot but even in the 1.0 C plot yield was reduced significantly.

13. Data from an airborne multispectral scanner showed slight, but detectable, increases in reflected visible and near infrared radiation with an increase in water stress of corn. These increases were small and would probably be less useful than observations in the thermal infrared portion of the spectrum for evaluating crop water status. Hail damage in corn, however, was readily detectable with the multispectral data.

14. Three of five crop temperature indices tested were highly correlated with the phenological growth stage of corn. These three indices could be used to monitor phenological development in corn and sorghum. Except under very severe conditions the water stress did not affect phenological development until near crop maturity.

Results of the studies summarized above suggest that crop temperature data can be used to assess crop water status. As such, crop temperature data can be used for scheduling irrigation; for detecting and monitoring effects of limited availability of water to crops, conditions which occur during drought and in semi-arid and arid regions; for evaluating the effectiveness of various irrigation scheduling techniques; for examining the uniformity of water application by various irrigation systems; for detecting soil areas with low water holding capacities; and as a means to select plant types which are most effective in tolerating or

avoiding shortages of water. Additional research is needed to further evaluate and quantify relationships between crop temperature and crop water status and to answer some of the questions raised in the conduct of our studies thus far.

Key words: Water stress, irrigation scheduling, crop temperature, infrared thermometry, plant temperature, canopy temperature, remote sensing, corn, sorghum, soybeans, irrigation, crop phenology, evapotranspiration, drought surveillance.

INTRODUCTION

In recent years, the amount of land being brought under irrigation has increased dramatically in the subhumid and semi-arid regions of the United States and throughout the world. In Nebraska alone, between 0.10 and 0.13 million ha are being added annually to the almost 3.4 million ha already under irrigation. This expansion of irrigation has created a greatly enlarged agricultural demand for water. At the same time, industrial, municipal and recreational demands for water have also grown.

The need for expanded food production to feed a hungry world has provided impetus for much of the growth in irrigation and has made agricultural use of water more economically competitive. This swelling demand for water, coupled with increasing energy costs to move the water, makes it imperative to refine or change many present irrigation practices. Practices such as irrigating by the calendar or applying water too liberally result in the waste of water, energy and fertilizer. Not only is excessive irrigation wasteful of resources and money but it often results in reduced yields. Leaching may remove nutrients from the root zone, roots may be poorly aerated and conditions favorable to development and spread of plant disease may develop.

Were it possible to reduce water application by 1 mm per day on the irrigated land of Nebraska alone through proper irrigation practices, over $1,500,000 a day in pumping costs could be saved. The water conserved on this one day would supply the annual water needs for an additional 1900 ha of land or supply water to a city of 250,000 people for a year.

Skillful, efficient management of water in agriculture will require knowledge of crop moisture status. Crop temperature is an indicator of the degree of moisture stress that the crop experiences. Thus, for example, the temperature of a crop may indicate the first exhibition of minor water stress. Irrigation could then be scheduled to replenish the soil moisture supply before further stress develops. In other cases application of irrigation water may be necessarily limited in order to reduce the overall demand for water. This increases the probability of moisture stress developing during the growing season. Because stress beyond a certain level can result in drastically reduced yields, it is necessary to carefully monitor the crop water status and to allocate the available water in such a way as to alleviate stress conditions before this critical level is reached. Crop temperature data may provide useful guidance in scheduling such irrigations.

Crop temperature data have several uses beyond that of irrigation scheduling. For example, they may serve as input into recently developed models for estimating evapotranspiration over large areas. Reliable estimates of the degree and extent of moisture stress induced in crops and rangeland by drought, can be made with surface temperature measurements. These data would be useful to government agencies and others charged with responsibility for predicting crop yields or assessing the economic impact of reduced yields resulting from drought.

Various crops exhibit different temperature responses to water stress. Crop temperature responses of many major agricultural crops grown in the Great Plains are not well understood. Such

responses can be affected by the various kinds of weather that occur in the Great Plains region. For example, it has been shown that crops in the Great Plains are often subject to very high water demand because of the advection of large quantities of sensible heat into the region by hot, dry winds coming from other, more arid regions. Temperature response under these circumstances is probably different than under other kinds of weather regimes. An understanding of these differences is vital if such temperature data are to be used in the applications decribed above.

The research reported in the ensuing Chapters of this report was conducted to provide information pertaining to the temperature response of some of the major agronomic crops, especially corn and sorghum, which are commonly grown in the Great Plains region under both irrigated and dryland conditions. The prime objective of the research has been: to evaluate the use of remotely sensed crop temperature data as a tool in the management of water resources. The subsidiary objectives without which the primary objective could not be achieved were: (1) to determine the temperature response of major agronomic crops to varying climatic and moisture conditions; (2) to test methods based on crop temperature and/or other readily measureable meteorological parameters for their accuracy in estimating crop stress or heat stress conditions and (3) to determine the feasibility of using crop temperature data as a guide for irrigation scheduling.

These objectives have been achieved for a few agronomic crops. The bulk of the research was conducted on sorghum and corn at the University of Nebraska Sandhills Agricultural Laboratory located

near Tryon, Nebraska (41° 37' N; 100° 50' W and 975 m above mean sea level) in 1978 and 1979. Some of the research work was done in 1978 at the Mead Agricultural Laboratory (41° 09' N, 96° 30' W and 354 m above mean sea level).

This final report consists of 11 chapters and 4 appendices. Each chapter has been written in a form roughly appropriate for publication. Most of the chapters will, in fact, be submitted to scientific journals in the near future. In essence then, these chapters may be considered to be "preprints." Hence, the reader may find occasional redundancy between chapters, especially with regards to the literature review and material and methods sections.

Chapters I and II contain data which were from preliminary studies in addition to data taken during the 1978 and 1979 studies. Chapter I describes the temperature response of several different types of vegetation growing under similar moisture and climatic conditions. In this chapter the agreement between crop temperatures measured with attached leaf thermocouples and with infrared thermometers is described.

In Chapter II thermal imagery and IR thermometer data are examined to determine if the crop temperature variability across a field at different times during the day may be indicative of the degree of water stress occurring. Findings on the optimum time of day for detecting maximum moisture stress by plant temperature measurement are also reported. The correlation between seasonal evapotranspiration amounts and the seasonal plant temperature differences (between stressed and non-stressed crops) is presented in Chapter II.

Chapter III summarizes the results of the 1978 studies on corn, sorghum and soybeans at Mead. The use of crop temperature data to schedule irrigation for these crops is discussed. Differences in the temperature response of the three crops to similar irrigation treatments are reported.

In Chapter IV the effects of water stress on crop height, plant phenology and grain yield are discussed. The effects of various irrigation treatments during critical growth stages on the temperature response and the grain yields are examined. Five different crop temperature indices are tested for their ability to predict phenological growth stage.

Chapter V contains information on the leaf and air temperature patterns in corn subjected to differential irrigation treatments. Mid-day differences in canopy temperature between stressed and non-stressed plants are examined as is the standard deviation of temperature in irrigated and non-irrigated areas. The difference between mid-day leaf and air temperature and the relationship to the detection of plant stress is evaluated. The relationship between the severity of stress and the time of day when plant temperatures become elevated is also discussed.

The temperature response of 3 hybrids of sorghum under a range of water stress conditions is reported in Chapter VI. Relationships between crop temperature, grain yield and evapotranspiration rates are evaluated in this chapter.

The results of using crop temperatures measured with an IR thermometer to schedule irrigation in corn are presented in Chapter VII. Included in this chapter are data on the affects of scheduling irrigation from predetermined canopy temperature levels on

final grain yields.

Differences in the temperature developed in 9 hybrids of corn at various levels of water stress and differences in canopy temperatures as a function of plant populations are given in Chapter VIII.

In Chapter IX a number of environmental factors which may affect the measurement of canopy temperatures with an infrared thermometer are described. The factors include: cloudiness, windspeed, solar azimuth, solar elevation, level of soil nitrogen and the direction from which the field is viewed by the IR thermometer.

Chapter X contains a discussion of a stress index which was developed to indicate the severity of water stress. This index involves temperature difference between stressed and non-stressed vegetation as measured during mid-morning and mid-afternoon.

The final Chapter evaluates the feasibility of using multispectral data obtained from overflights by NASA aircraft as a means of assessing the moisture status of corn and, also, to detect hail damage.

We wish to express our sincere appreciation to Dr. Darrell Watts, Dr. Wayne Kroutil and Mr. William Kranz of the Agricultural Engineering Department UNL/IANR who designed and operated the irrigation systems at SAL. These individuals also provided valuable assistance in the management of the research plots and collected data which they have graciously made available to us. We also appreciate the cooperation of Dr. Charles Y. Sullivan of the Department of Agronomy who helped design experiments in some of the plots. We are grateful for the excellent cooperation of

several individuals at the North Platte Experiment Station -- especially Mr. Neil Baxter, Dr. Gary Hergert, Mr. Dennis Wilson and Mr. Ed Schwartz. Without their valuable assistance it would have been extremely difficult to accomplish our research objectives. We acknowledge the helpful comments and suggestions of Dr. Shashi B. Verma and Dr. John Norman. Mr. Jim Hines assisted us in our data computations and analysis. Mr. Dale Sandin and Mr. Tom Keber provided technical assistance in conduct of the experiments. Ms. Lee Donelson and Ms. Norma Gottschlak assisted in maintenance of the research plots and in several data collecting activities. Wayne Hall, Gary Lewis and Karen Stork of the Nebraska Water Resources Center offered helpful suggestions in developing the proposal and were very cooperative in making necessary changes in the conduct of the research and in preparation of the final report. Mrs. Roberta Sandhorst, Mrs. Nancy Brown and Mrs. Betty James have, with good humour, typed the many drafts of this report. Marty Shaneyfelt drew the majority of the figures appearing in this report.

The contents of this publication do not necessarily reflect the views and policies of the Office of Water Research and Technology, U.S. Department of the Interior, nor does mention of trade names or commercial products constitute their endorsement or recommendation for use by the U.S. Government.

This completion report was sponsored in part by the Nebraska Water Resources Center, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

CHAPTER I

PLANT AND AIR TEMPERATURE PATTERNS IN ALFALFA, CORN, GRASS, SORGHUM AND SOYBEANS AS MEASURED WITH THERMOCOUPLES AND INFRARED THERMOMETERS

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ABSTRACT

Results of studies comparing temperature measurements made with an infrared thermometer and with attached leaf thermocouples have raised several questions, such as: 1) to what extent do crop type, leaf area, percent cover and stage of growth affect agreement between the two methods of measurements?; 2) where should leaf thermocouples be placed in a plant canopy in order to provide a representative measure of crop temperature?; 3) how does moisture stress influence the measurement of crop temperature?; 4) how does planting pattern affect crop temperature measurement? A study designed to answer these questions and to provide further understanding of factors that affect the agreement of leaf thermocouples and infrared thermometers is reported here.

Plant and air temperatures were measured in Nebraska on plots of alfalfa, corn, grass, sorghum and soybean with an infrared thermometer (IRT) and with evanohm-constantan thermocouples at three levels within the canopy. Data were collected during three 24-hour periods in 1976 and again throughout the 1978 growing season.

Prior to the achievement of 75% crop cover, infrared thermometer temperature (T_{IR}) during daytime was consistently warmer than the thermocouple temperature (T_{TC}) of sunlit leaves. The

difference in results between the two methods was dependent on canopy cover. With greater than about 80% cover, T_{IR} was generally within ±1 C of sunlit leaves.

At night, the lower leaves of all crops were warmer than the upper leaves. T_{IR} was 1 to 3 C warmer than the upper leaves, but was generally within 1 C of the lower leaves. This suggests that, at night, T_{IR} is influenced by soil temperature and that better estimates of plant temperatures are obtained with leaf thermocouples than with infrared sensing devices, especially for vertical viewing angles.

Daily leaf and air temperature profiles in all crops were similar. Profiles tended to be lapse before crop cover was complete and inverted later in the season.

T_{IR} of fully irrigated corn agreed with T_{TC} to within 1.2 C during the daytime. The daytime agreement between T_{IR} and T_{TC} among stressed corn plants was 2.6 C. The mid-day differences in T_{TC} between two non-irrigated plants spaced 2 meters apart was as great as 5.9 C. Thus, sampling problems will make it difficult to estimate an average T_{TC} in moisture stressed crops. At mid-day alfalfa was about 1.0 to 1.5 C cooler than soybeans, 3.5 C cooler than sorghum and 8.5 C cooler than grass. This suggests that the rate of evapotranspiration in alfalfa was greater than soybeans which was greater than sorghum. Evapotranspiration rate in the grass was the lowest of any of the crops.

INTRODUCTION

Many factors, including soil temperature, percent cover and leaf area index, may influence the agreement between crop

temperature as measured with leaf thermocouples (T_{TC}) and with an infrared thermometer (T_{IR}). One would expect that the factors named should affect mainly T_{IR} because of the area "viewed", and consequently the radiation sensed, by the infrared thermometer. However, the agreement may be affected, as well, by sampling difficulties inherent in the use of attached leaf thermocouples, a very large number of which may be needed to obtain an average canopy temperature.

Lourence et al. (1965) found that the major disagreement between T_{IR} and T_{TC} in tall fescue occurred during the daylight hours. They stated that the leaf thermocouples overestimated the surface temperature of the crop due to radiation errors. At night, however, T_{IR} was generally warmer than T_{TC}.

Landsberg et al. (1974) used two sets of five thermocouples each attached to leaves spaced evenly through the canopy of an apple tree in order to estimate the average leaf temperature. They also measured the temperature of sunlit and shaded leaves with an infrared thermometer (IRT). Their results show that the average leaf temperature, measured with the randomly distributed thermocouples, was within the range of temperature of sunlit and shaded leaves measured with the IRT.

Blad and Rosenberg (1976) found that the temperature of alfalfa measured with leaf thermocouples and with an IRT failed to agree consistently to within 1 to 2 C, although occasionally, agreement was better than 0.5 C. Agreement improved as the crop cover increased and it was generally best during mid and late afternoon and worst in the early morning.

There is, as yet, insufficient information concerning the

influence on T_{IR} of the soil temperature, percent cover or type of canopy. Blad et al. (1975), for example, observed that the type of canopy and the percent cover in millet and sorghum fields affected the agreement between T_{IR} and T_{TC}. Agreement was better for millet than for sorghum, especially late in the growing season when the crop was well established. They also found that the daytime agreement was much better (1 C) than that at night (1 to 3 C).

MATERIALS AND METHODS

Studies were conducted in 1976 at the University of Nebraska Agricultural Meteorology Laboratory near Mead, Nebraska (41° 09' N; 96° 30' W; 354 m above m.s.l.) and at the Sandhills Agricultural Laboratory (SAL) near Tryon, Nebraska (41° 37' N; 100° 50' W; 975 m above m.s.l.) in 1978.

1976 Study

In the Mead experiment measurements were made on plots of alfalfa (*Medicago sativa* L.); sorghum (*Sorghum bicolor* L. Moench); grass (*Festuca elatior*) and soybean (*Glycine max* L.). Each plot was ten meters long (N to S) and three meters wide (E to W).

Sorghum and soybeans were both planted on May 21, 1976 in two different planting systems, row and broadcast. Rows were 50 cm wide and the plants were spaced about 3 cm apart. Seeds of sorghum and soybean were also broadcast in a planting pattern that assured early and complete ground cover (Fig. 1). All plots were irrigated to field capacity on July 21. No additional irrigations were made until the end of the experiment.

Crop temperature, soil moisture, plant height and percent

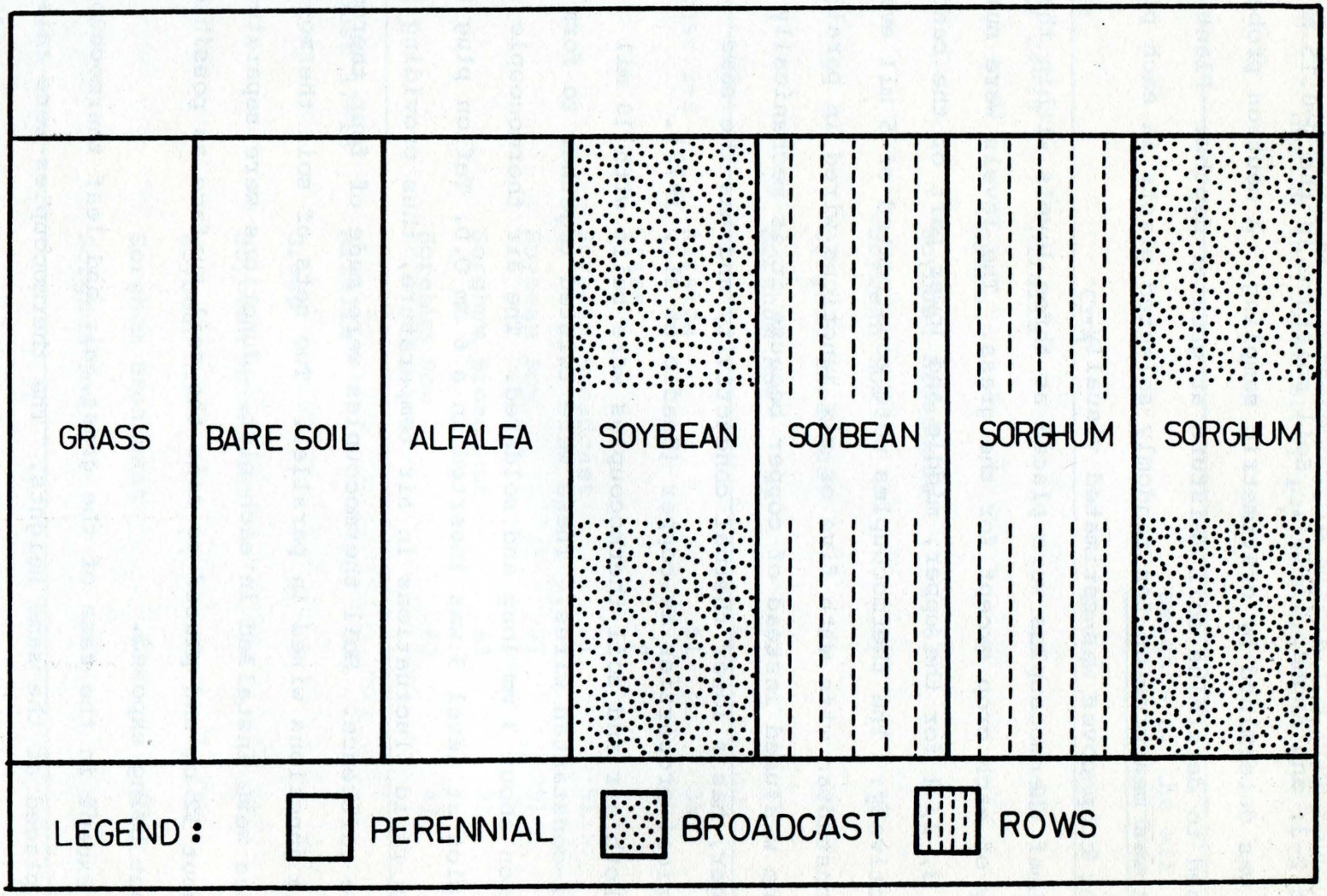


Fig. 1. Field layout of the various experimental plots and planting patterns at Mead (1976).

crop cover were measured during each of three periods (July 24-25; August 2-3; and August 17-18). Soil moisture in the 0-0.15 m layer was determined by gravimetric sampling. A neutron probe was used to determine soil moisture at greater depths. Plant height was measured on ten randomly selected plants in each plot. Percent crop cover was estimated visually.

Leaf thermocouples were placed at three levels within the canopy of each crop except for the grass. The levels were numbered 3, 2, 1 for the upper, middle and lower part of the canopy, respectively. The thermocouples were constructed of 5 mil evanohm-constantan wire with five or six junctions wired in parallel. Evanohm was used instead of copper because it is mechanically stronger, has a lower thermal conductivity and has the same electrical properties as copper (Beadle et al., 1973).

Both air and soil thermocouples were built with 10 mil copper-constantan wires. These were twisted together to form a junction about 3 mm long and soldered. The air thermocouple in each plot at level 3 was inserted in a 6 mm O.D. Teflon plug to dampen rapid fluctuations in air temperature, thus providing a stable reference. Soil thermocouples were made of four thermocouple junctions wired in parallel. Two sets of soil thermocouples were installed in each plot. Junctions were separated by about 12 cm and placed as near the soil surface as possible without being exposed.

Except in the case of the grass, air and leaf thermocouples were placed at the same heights. The thermocouples were raised as the crops grew (Table 1). The air thermocouples were radiation

Table 1. Heights of air thermocouple within the crop canopy during the three study periods in 1976.

Date	Crop	Heights of the air thermocouples in cm from ground Level 3	Level 2	Level 1
July 24-25	Alfalfa	43	23	11
	Grass	6		
	Soybean Broadcast	63	43	19
	Soybean Row	59	39	19
	Sorghum Broadcast	63	47	31
	Sorghum Row	63	47	31
August 2-3	Alfalfa	51	35	19
	Grass	9		
	Soybean Broadcast	71	51	27
	Soybean Row	71	51	27
	Sorghum Broadcast	63	27	31
	Sorghum Row	63	47	31
August 17-18	Alfalfa	53	37	21
	Grass	9		
	Soybean Broadcast	79	55	35
	Soybean Row	79	55	35
	Sorghum Broadcast	63	67	31
	Sorghum Row	63	47	31

shielded with a Mylar shield 8 cm in diameter.

Difficulties were encountered in finding a practical and efficient method to attach thermocouples to the leaves. The best results were obtained in the following way: the thermocouple junctions were bent at an angle of 60-90 degrees about 3 mm from their beads. A small piece of filament tape was placed several mm from the bead and used to hold the thermocouple against the leaf. An additional strip of tape was placed 1-2 inches from from the junction for mechanical support. In this way the thermocouple was, essentially, spring loaded against the leaf.

A Barnes model IT-3 IR thermometer was used during the 1976 study. The infrared thermometer (IRT) was mounted 3 m above the ground on an arm extending from a cart. The cart was pulled manually between predetermined stations in each plot. The IRT "viewed" the ground vertically. In the soybean and sorghum row plots, the IRT was placed to view one area within the rows and another area between the rows. Results showed that the temperature of these two areas were similar.

The IR thermometer was calibrated using a procedure similar to that of Conaway and van Bavel (1966). That procedure is described in detail by Blad and Rosenberg (1976). The emissivity of each crop was estimated by the method of Fuchs and Tanner (1966) except that a large plastic garbage can, covered on the inside with aluminum foil, was used instead of the "pop tent." The container had one hole in the closed end where the sensing head of the IRT was placed.

Emissivity of the crops was determined on the night of August 23, 1976 when the sky was completely clear. Readings

were made over a normal sorghum crop and again with the heads removed. Emissivity was calculated separately for each of the two planting patterns (row and broadcast) in soybean and sorghum (Table 2).

1978 Study

In the study conducted at the Sandhills Agricultural Laboratory, plant temperature measurements were made on a plot of corn (Zea mays, c.v. Pioneer 3780) which was differentially irrigated. The plot measured 27 meters (N to S) by 19 m (E to W). The plot contained 24 rows spaced at 0.76 m. The differential irrigation consisted of applying full irrigation (100% of transpiration demands) to row 1 and applying progressively less moisture to each succeeding row until, in rows 22 to 24, essentially no irrigation water was received.

Leaf temperatures were measured at three levels within the canopy on rows 2, 6, 10, 14, 18 and 22. Leaf temperatures were recorded at hourly intervals throughout the growing season. This experiment is described more fully in Chapter 2.

A Telatemp Model 44 and a Barnes PRT-5 were used to measure crop temperature. A crop emissivity of 0.97 was established on the night of June 3. The IRT was used with viewing angles ranging from 15 to 22 degrees from the horizontal.

RESULTS AND DISCUSSION

Agreement Between Leaf Thermocouples and Infrared Thermometers

One of the major problems associated with measuring canopy temperatures with IRT's is distinguishing the true plant temperatures when bare soil is also viewed by the sensor. The degree

Table 2. Emissivity of bare soil and six vegetative surfaces, determined on August 23, 1976.

Crop	Planting Pattern	Emissivity	
		Normal	Heads Removed
Alfalfa		.981	
Grass		.977	
Bare Soil		.954	
Soybean	Rows	.976	
Soybean	Broadcast	.971	
Sorghum	Rows	.971	.974
Sorghum	Broadcast	.971	.974

to which bare soil biases canopy temperature measurement depends on several factors, including viewing angle of the IRT, temperature and emissivity differences between soil and the canopy, percentage of soil seen by the IRT and solar elevation angle. Millard et al. (1978) have suggested that, especially when crop cover is sparse, a relationship between canopy temperature, plant temperature and percent bare soil is needed. This need is felt particularly when canopy temperatures measured by airborne sensors are to be correlated with actual plant temperatures. No such relationship has yet been reported in the literature.

Large differences in the soil surface temperature of irrigated and non-irrigated areas occur following irrigation. For example, on June 9, 1978, prior to irrigation, the difference in soil surface temperature, as measured with an IRT, between an irrigated and non-irrigated area was 0.5 C. Following irrigation on the next day, the soil surface temperatures were 15.9 C lower in the irrigated area.

The Mead experiment in 1976 did not begin until 75% crop cover had been reached. In 1978 at SAL, data were collected from the time of corn crop emergence. Until 40% cover was achieved, bare soil caused IRT temperatures to differ by as much as 13 C from thermocouple measurements of non-stressed sunlit leaves (Fig. 2).

Between 40 and 80% crop cover, T_{IR} temperatures tended to be lower than T_{TC} values of sunlit leaves. T_{IR} values probably reflect the influence of the cooler shaded soil and the shaded leaves of the lower canopy.

After 80% crop cover was achieved, the IRT viewed almost no

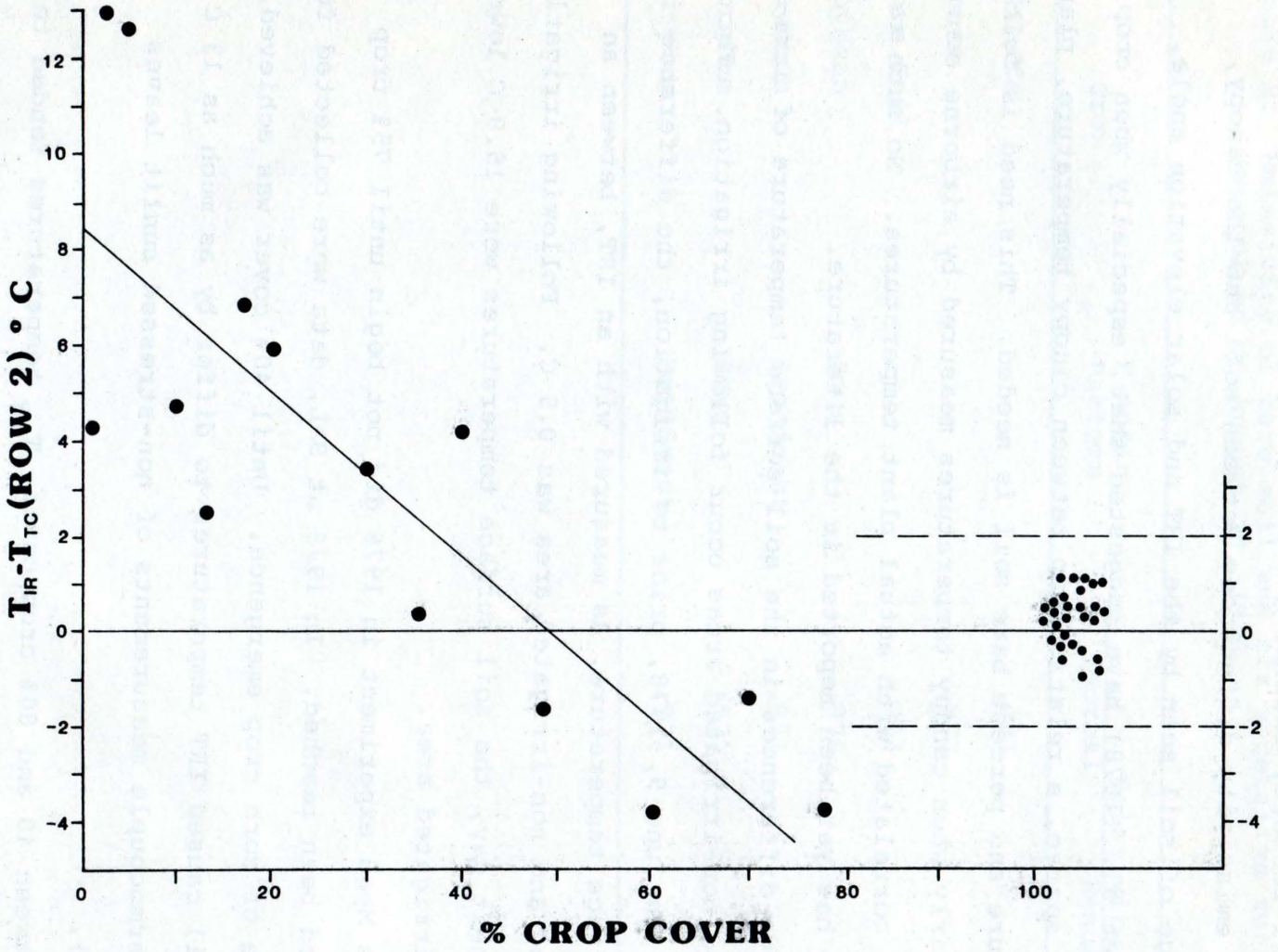


Fig. 2. Canopy temperatures of corn as measured with an IR thermometer (T_{IR}) and with leaf thermocouples (T_{TC}) as influenced by percent crop cover. Data were obtained in 1978 at the University of Nebraska Sandhills Agricultural Laboratory.

soil. Then the IRT and leaf thermocouple temperatures agreed to within 1.2 C (Fig. 3). This agreement is, however, dependent on plant moisture stress since stress increases the plant to plant temperature variability. T_{TC} values of sunlit leaves in stressed corn plants 2 m apart differed as much as 5.9 C. Thus to find representative areas for sampling with thermocouples is very difficult, especially if plants are subjected to water stress. Infrared thermometry appears, therefore, the more likely method for measuring average canopy temperature of crops under moisture stress.

A typical daily pattern for T_{IR} and T_{TC} within the canopy of row-planted soybeans is given in Fig. 4. T_{IR} agreed better with T_{TC} of the sunlit leaves than with T_{TC} values for either of the deeper levels.

A different pattern of agreement between values of T_{IR} and T_{TC} was observed in the plots of row-planted sorghum (Fig. 5). T_{IR} agreed about equally well with thermocouple temperatures at the bottom, middle and top of the canopy. Since the temperature at these three levels was nearly isothermal during each study period, it appears that placement of thermocouples in canopies with structure similar to sorghum may be less critical than in crops with canopies similar to those of soybean and alfalfa.

T_{IR} and T_{TC} did not agree well in the grass plot. A layer of dry grass near the surface of the ground, tended to "mulch" the soil. This non-transpiring material became warmer than either the soil surface or the green grass with the result that, under conditions of high radiative flux densities, the IRT temperatures were as much as 6 C greater than those measured with thermocouples.

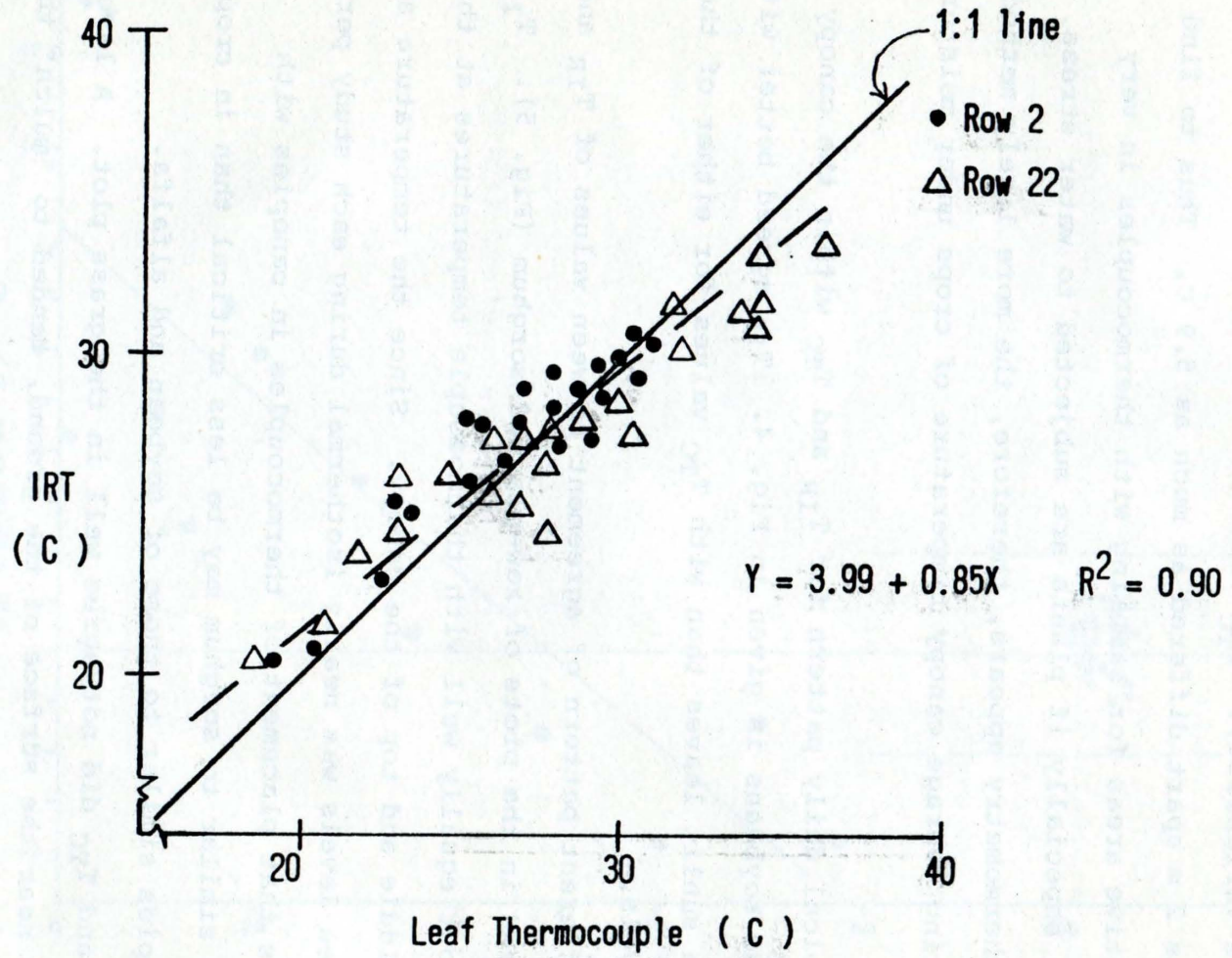


Fig. 3. Mid-day canopy and leaf temperatures of corn as measured with an IR thermometer (IRT) and leaf thermocouples, respectively. Data are from row 2 (non-stressed) and row 22 (stressed) on 26 clear days between July 19 and September 6, 1978.

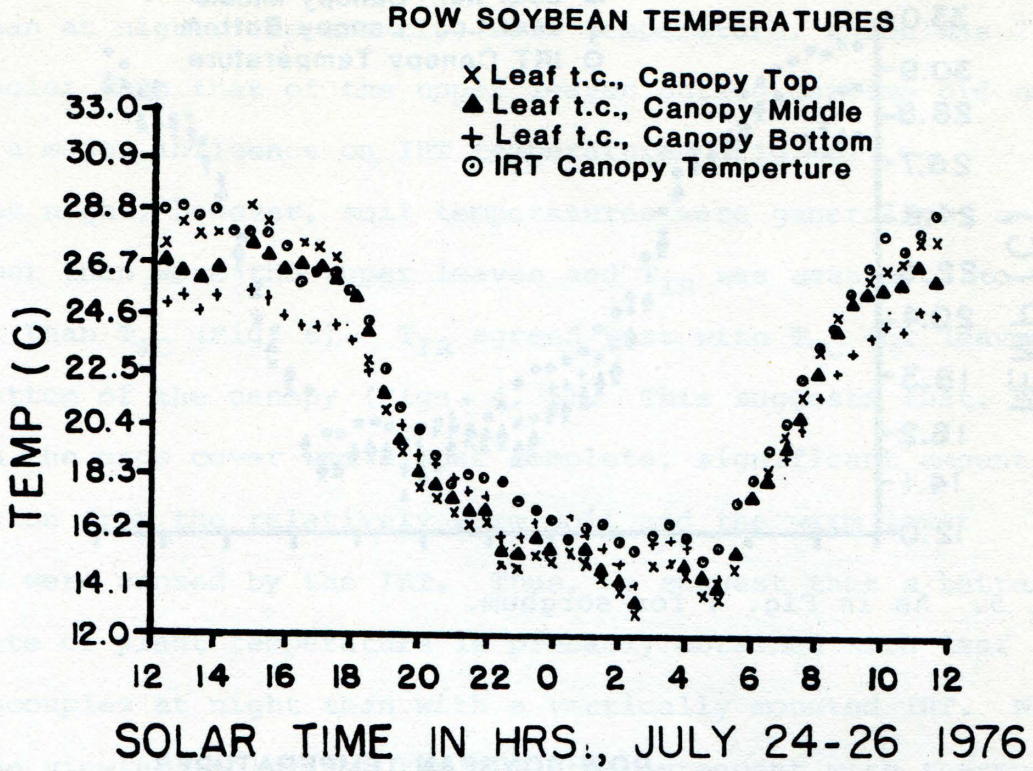


Fig. 4. Daily pattern of the canopy temperature of soybeans as measured with an IR thermometer (T_{IR}) and with leaf thermocouples (T_{TC}) placed at three levels within the soybean canopy. Data were obtained at the University of Nebraska Mead Field Laboratory in 1976.

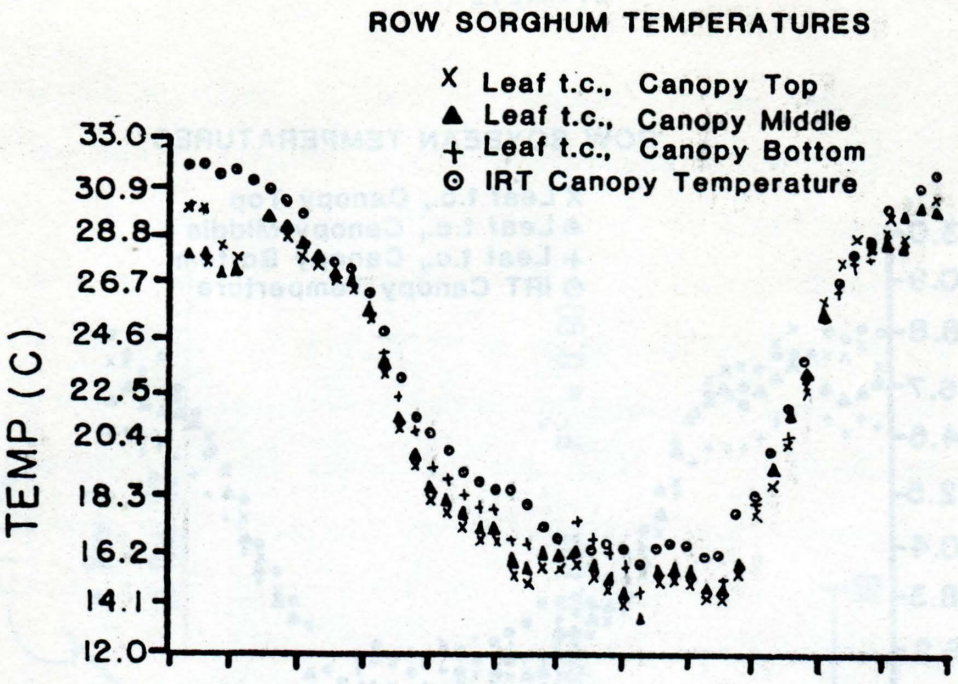


Fig. 5. As in Fig. 4 for sorghum.

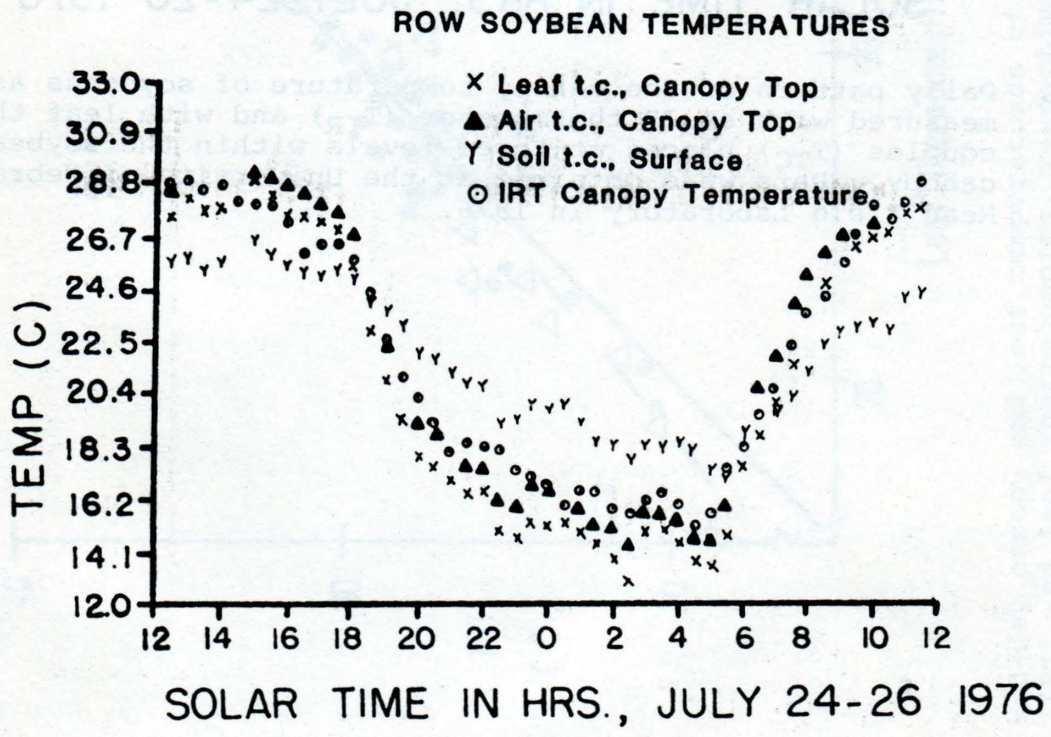


Fig. 6. As in Fig. 4 for T_{TC}, T_{IR}, air temperature and soil temperature.

Daily Patterns of Air Temperature Within Canopy

Air temperature patterns were similar for all crops after 80% cover had developed. Daytime profiles were generally inverted and nighttime profiles were nearly isothermal. This general pattern is illustrated with data for corn (Fig. 7). Prior to 80% crop cover, air temperature profiles in the corn canopy were lapse throughout the day changing to a slight inversion at night (Fig. 8).

Comparison of T_{IR}-Sensed Temperatures in Various Crops

Alfalfa was the coolest of the four crops grown in 1976 according to IRT measurements (Fig. 9). At midday soybeans were about 1 to 1.5 C warmer, sorghum was about 3.5 C warmer and grass was approximately 8.5 C warmer than alfalfa. Our results for sorghum and soybeans agree with those of Heilman et al. (1976) who found that soybeans were about 2 C cooler than sorghum. The elevated T_{IR} in grass was probably due to the influence of the layer of non-transpiring dead grass mulch which covered the soil surface. At night IRT temperatures were virtually identical in each of the four crops.

In general, the temperature of a plant is inversely related to its transpiration rate. Based on this premise, we estimate that the water use for the four crops was in the following order: alfalfa > soybeans > sorghum > grass.

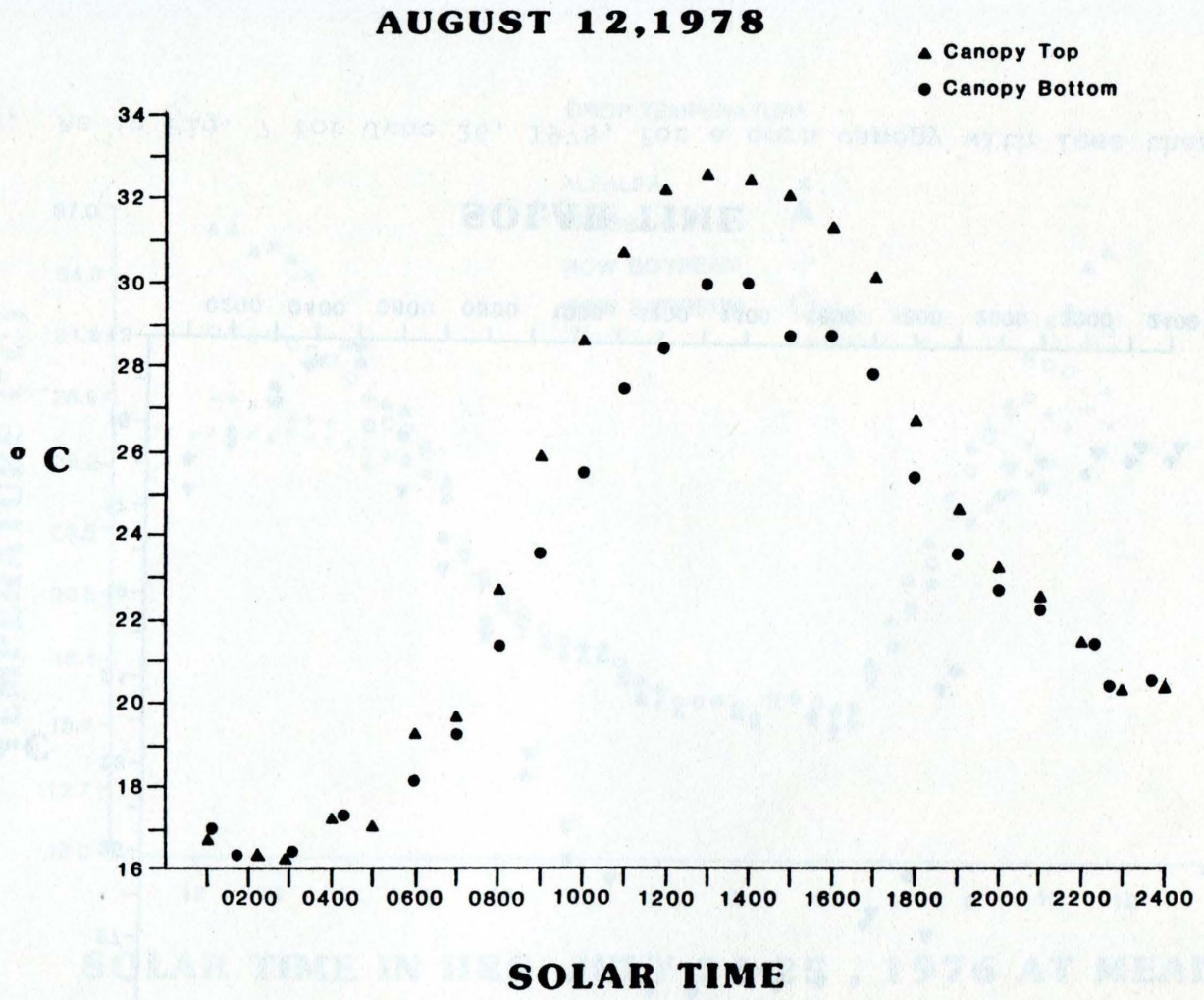


Fig. 7. Air temperature at the top and bottom of a corn canopy with complete cover on August 12, 1978. Data are from the Sandhills Agricultural Laboratory.

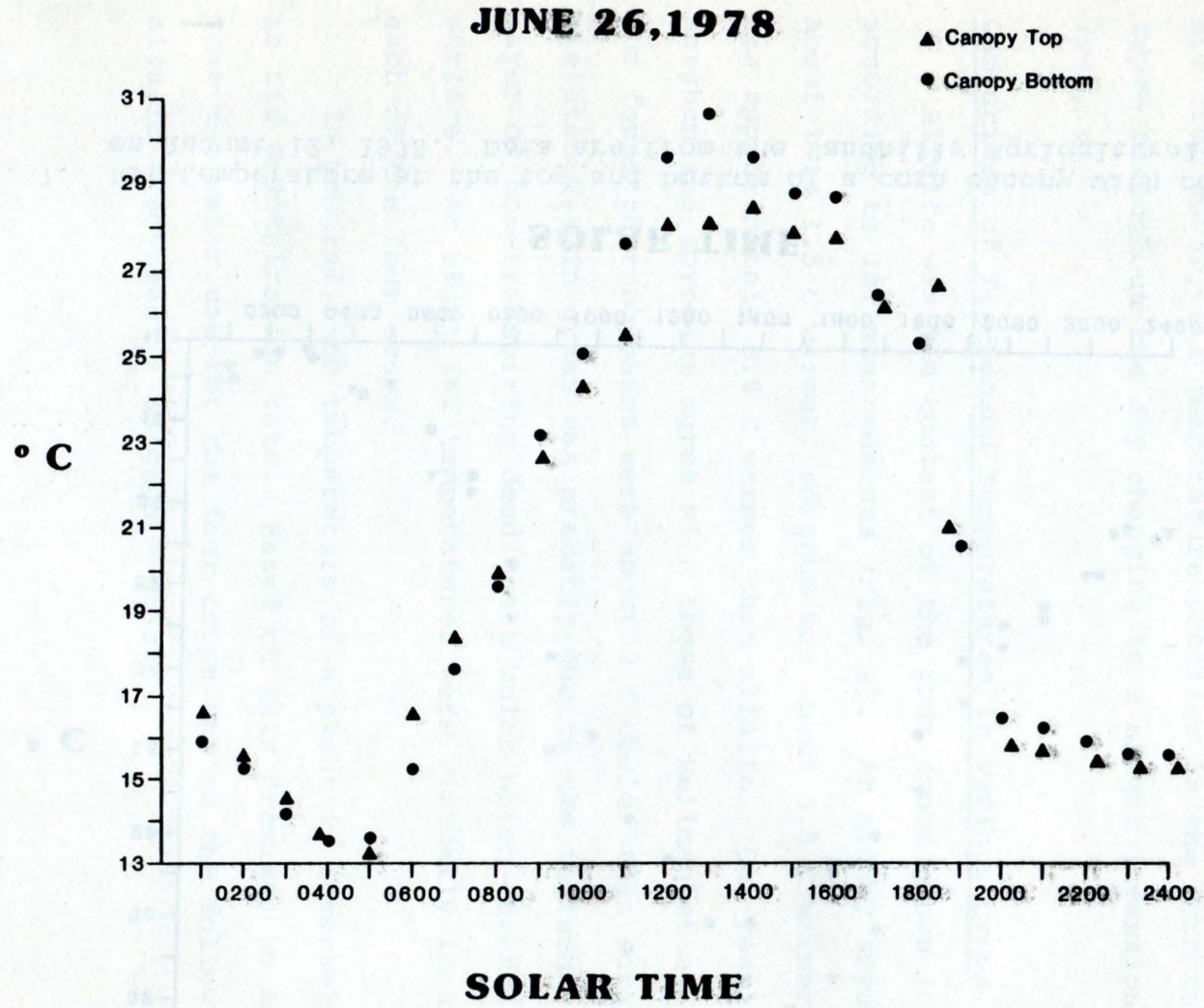


Fig. 8. As in Fig. 7 for June 26, 1978, for a corn canopy with less than 80% crop cover.

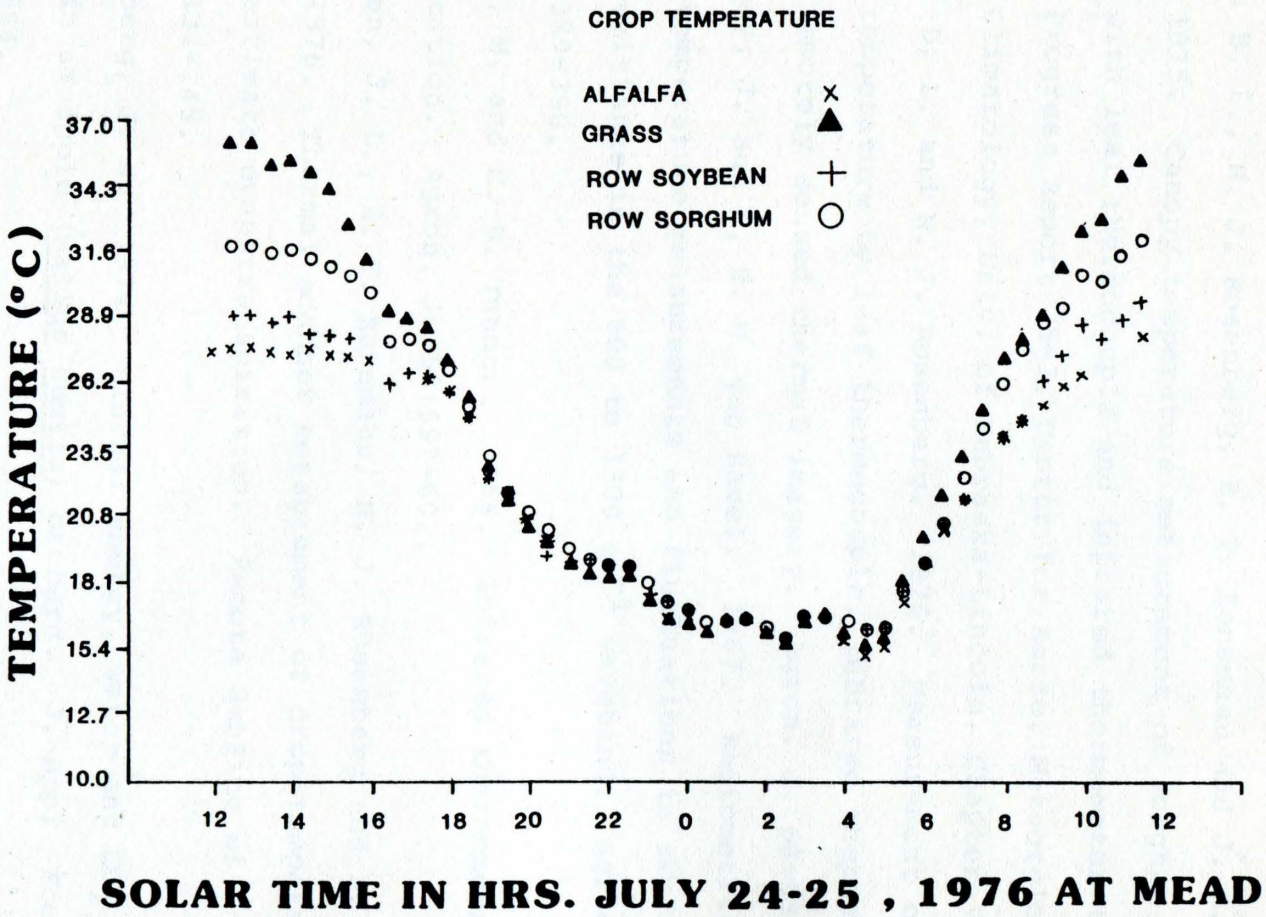
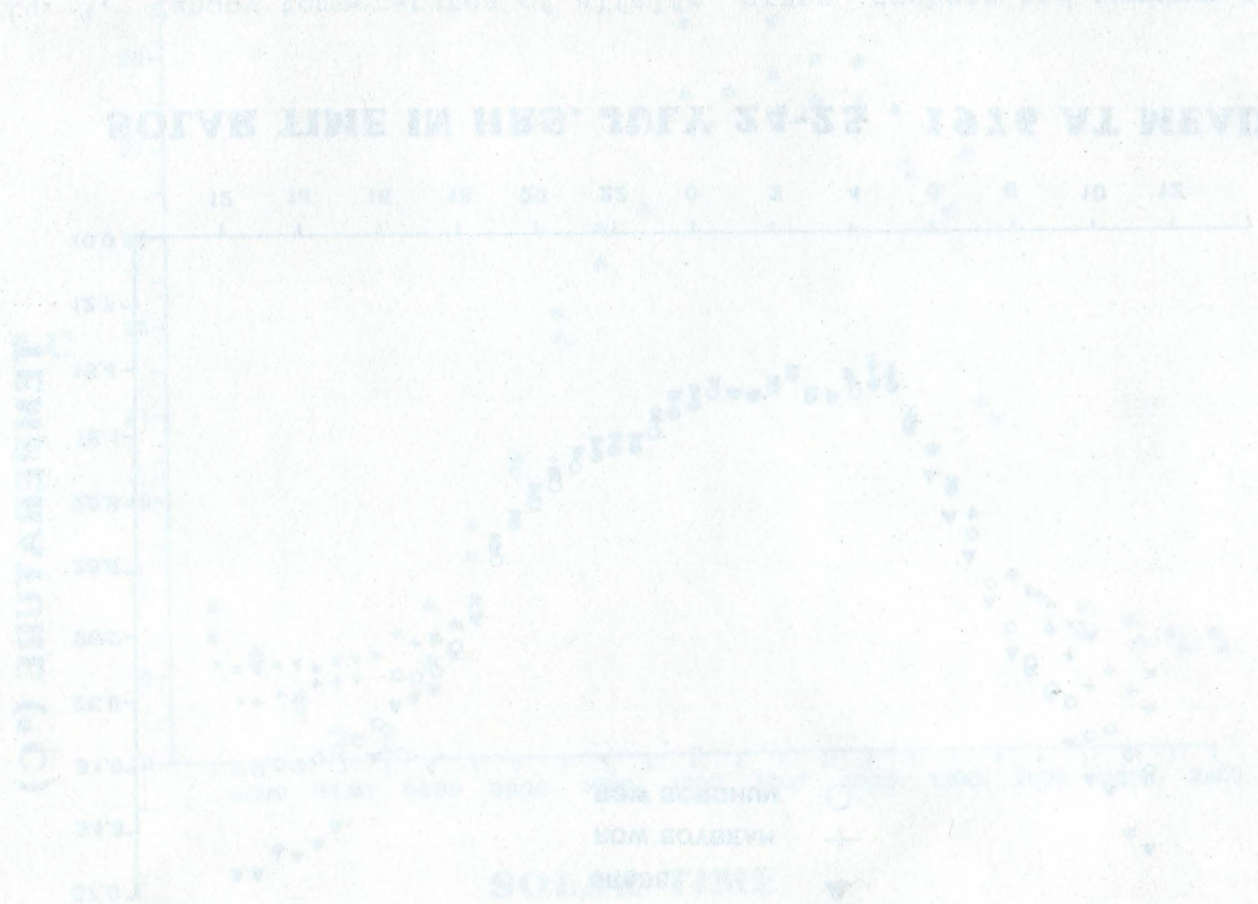


Fig. 9. Canopy temperatures of alfalfa, grass, soybean and sorghum as measured with an IR thermometer (T_{IR}). Data are from Mead Field Laboratory in 1976.



REFERENCES

Beadle, C. L., K. R. Stevenson and G. W. Thurtell. 1973. Leaf temperature measurement and control in a gas-exchange cuvette. Canada J. Plant-Sci. 53:407-412.

Blad, B. L., N. J. Rosenberg, E. T. Kanemasu and J. L. Heilman. 1975. Canopy temperature measurement of sorghum and millet with leaf thermocouple and infrared thermometer techniques. Progress Report 75-3, Center for Agric. Meteorology and Climatology, Univ. of Nebraska-Lincoln, Chapter V.

Blad, B. L. and N. J. Rosenberg. 1976. Measurement of crop temperature by leaf thermocouple, infrared thermometry and remotely sensed thermal imagery. Agron. J. 68:635-641.

Conaway, J. and C. H. M. van Bavel. 1967. Radiometric surface temperature measurements and fluctuations in sky radiant emittance in the 600 to 1300 cm^{-1} waveband. Agron. J. 59: 389-390.

Fuchs, M. and C. B. Tanner. 1966. Infrared thermometry of vegetation. Agron. J. 58:597-601.

Heilman, J. L., E. T. Kanemasu, N. J. Rosenberg and B. L. Blad. 1976. Thermal scanner measurement of crop temperatures to estimate evapotranspiration. Remote Sensing of Environ. 5: 137-145.

Landsberg, J. J. 1974. Diurnal energy, water and CO_2 exchanges in an apple (Mallus Pumila) orchard. J. Appl. Ecol. 12:659-684.

Lourence, F., W. O. Pruitt, and S. W. Burrage. 1965. Measurement of grass temperatures with thermocouples and infrared techniques. In Investigation of Energy, Momentum and Mass Transfer Near the Ground. Final Report to USAECOM Atmos. Sci. Lab., Fort Huachuca, Arizona. University of California, Davis.

Millard, J. P., R. D. Jackson, R. C. Goettelman, R. J. Reginato and S. B. Idso. 1978. Crop water-stress assessment using an airborne thermal scanner. Photogrammetric Engr. and Remote Sensing. 44:77-85.

CHAPTER II

REMOTE SENSING OF CROP MOISTURE STATUS

B. L. Blad, B. R. Gardner, D. G. Watts and N. J. Rosenberg

ABSTRACT

Remotely sensed thermal imagery may provide a means to assess the extent and severity of water stress on crops over a large area. This would make remote sensing a useful tool for monitoring the effects of drought on crops. Before that becomes a reality, however, crop temperature-moisture stress relationships must be determined. The purposes of this study were to determine some of these relationships and to evaluate some of those factors which will affect the crop temperature data.

Studies were conducted on sorghum in 1974 and on corn in 1978 at two different locations in Nebraska. Plant temperatures were obtained with thermal imagery, with infrared thermometers and with leaf thermocouples. Irrigation treatments in 1978 were designed to permit a plot to receive either full irrigation or to apply a water gradient across the plot during the vegetative pollination and grain fill periods. The gradient treatments resulted in fully-irrigated plants on one side of the plot and dryland plants on the other side.

An examination of the thermal imagery obtained over irrigated and non-irrigated sorghum in 1974 showed that the non-irrigated sorghum plots were at approximately the same temperature as the irrigated plot until mid-afternoon. From then until late evening the non-irrigated sorghum was warmer. There was relative uniformity of temperature across the irrigated sorghum plot but temperatures

were variable across a non-irrigated plot.

The difference in temperature (ΔT) between stressed and non-stressed corn was as great as 12.8 C during mid-afternoon readings. There was a wide range in ΔT from plot to plot, however, reflecting the variability of available soil moisture. Plant height was reduced during the vegetative growth stage by water stress.

Clouds caused more of a decrease in the temperature of stressed plants than of non-stressed plants. The optimum time of day for detecting maximum plant temperature was between 1300 and 1500 solar time. Thus, a good time for making plant temperature measurements in water stress studies would be 1400.

The temperature of well-watered corn as measured with attached leaf thermocouples was within ± 1.2 of the temperature measured with an IR thermometer. The agreement was ± 2.6 C among the stressed plants. Above 27 C, IRT temperatures were slightly cooler than the temperature of the upper sunlit leaves and below 27 C, they were slightly warmer.

Differences in seasonal evapotranspiration (ET) between well-watered and stressed plants were highly correlated with the seasonal accumulation of ΔT.

INTRODUCTION

Reliable estimates of the degree of crop stress occurring at any specified time should be useful to government agencies and others charged with predicting crop yields or assessing the economic impact of reduced yields due to drought. Increasing attention is being given to evaluating the use of remotely sensed crop temperature data for monitoring the extent and severity of drought.

Researchers have demonstrated that when soil water becomes limited, water-stressed plants become warmer than well-watered plants (Tanner, 1963; Palmer, 1965; Bartholic et al., 1972; Ehrler et al., 1978). Although the feasibility of using remotely sensed crop canopy temperature data as an indicator of plant water status has been demonstrated, quantitative data relating canopy temperature to the development of crops over a complete growing season is sparse. Idso et al. (1977) and Jackson et al., (1977) have reported seasonal results for durum wheat (Triticum durum Desf.) grown in Phoenix, Arizona.

The purposes of the study reported here were as follows: 1) to observe the behavior of irrigated and non-irrigated corn (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) with respect to crop temperature; 2) to evaluate the effect of clouds on the temperature of stressed and non-stressed corn and sorghum plants; 3) to determine the optimum time of day to use crop temperature data for detection of maximum plant water stress; 4) to compare the temperature of stressed and non-stressed vegetation as measured with leaf thermocouples with those measured with an infrared thermometer and 5) to describe evapotranspiration (ET) as a function of cumulative seasonal crop temperature data.

MATERIALS AND METHODS

A field of 1.82 ha at the University of Nebraska Agricultural Meteorology Research Laboratory at Mead, Nebraska (41° 09' N; 96° 30' W; 354 m above m.s.l.) was studied with thermal imagery. Sorghum (Sorghum bicolor Moench cv. 'Rs633') was planted on May 16, 1974 in north-south rows on 51 cm centers with 10 plants/m or row.

The field was sprinkler irrigated weekly (about 3.6 cm per application) between June 18 and August 2. The surrounding fields were also planted to sorghum but were not irrigated.

During the growing season, crop temperatures were measured from altitudes of 610 and 1220 m with a thermal scanner* in an aircraft furnished by the Remote Sensing Institute of South Dakota State University. Flight lines were parallel to field rows at the three sites. Flights were made on August 12 and August 26. Tempertures were measured in the 8.7 to 11.5 μm wavelength band at a scanning rate of 80 scans per sec. The temperature resolution of the scanner was 0.4 C and the spatial resolution was 16 cm per 100 m of altitude. Additional information concerning this experiment can be found in Rosenberg et al. (1975).

Most of the data reported here were obtained during the 1978 growing season at the University of Nebraska Sandhills Agricultural Laboratory (SAL) (41° 37' N; 100° 50' W; 975 m above m.s.l.), located about 40 miles north of North Platte, Nebraska.

Canopy temperatures were measured each day throughout the 1978 growing season. Measurements were made with an infrared thermometer (IRT) between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 of each plot. Two infrared thermometers were used: a Telatemp model 44 and a Barnes PRT-5. One plot used for IRT measurements was also instrumented with leaf thermocouples at the bottom, middle and top of the canopy on rows 2, 6, 10, 14 and 22. Net radiation was also measured on this plot with a Middleton Model CN6 miniature net radiometer at an elevation of

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*Daedalus Enterprises, Inc., Ann Arbor, Michigan.

3 m above the soil surface.

Soil moisture was measured weekly in each plot with a neutron probe in the same rows as were used for temperature measurements at depths of 15, 30, 60 90 and 150 cm. Rainfall and irrigation were measured with rain gauges installed adjacent to each neutron access tube. The gauges were raised, as the season progressed, to maintain the "catch height" just above the top of the canopy.

Line Source System

Hanks et al. (1976) reported the development of a line source irrigation system. When irrigation sprinklers are spaced closely along a single pipeline, the resulting depth of water application is essentially constant along the line but decreases with distance from it. This results in a "gradient" water application ranging from a maximum at the line to zero at a distance equal to the wetted radius or "throw" of the sprinkler. The actual distance involved depends on the design of the sprinkler system and on wind speed and direction during operation of the system.

Figure 1 shows the growth pattern that might result if such a system were used to irrigate a crop throughout a growing season. The crop near the sprinkler line would receive "full" irrigation while proportionately smaller irrigation amounts would be received by the crop at greater distances from the line. Beyond the reach of the sprinklers, the crop would have available only stored soil water and rainfall to meet its requirements. Single-sprinkler lines or "line sources" have been used by researchers to provide varying quantities of water to experimental plots.

Where crops are planted parallel to the sprinkler line, each

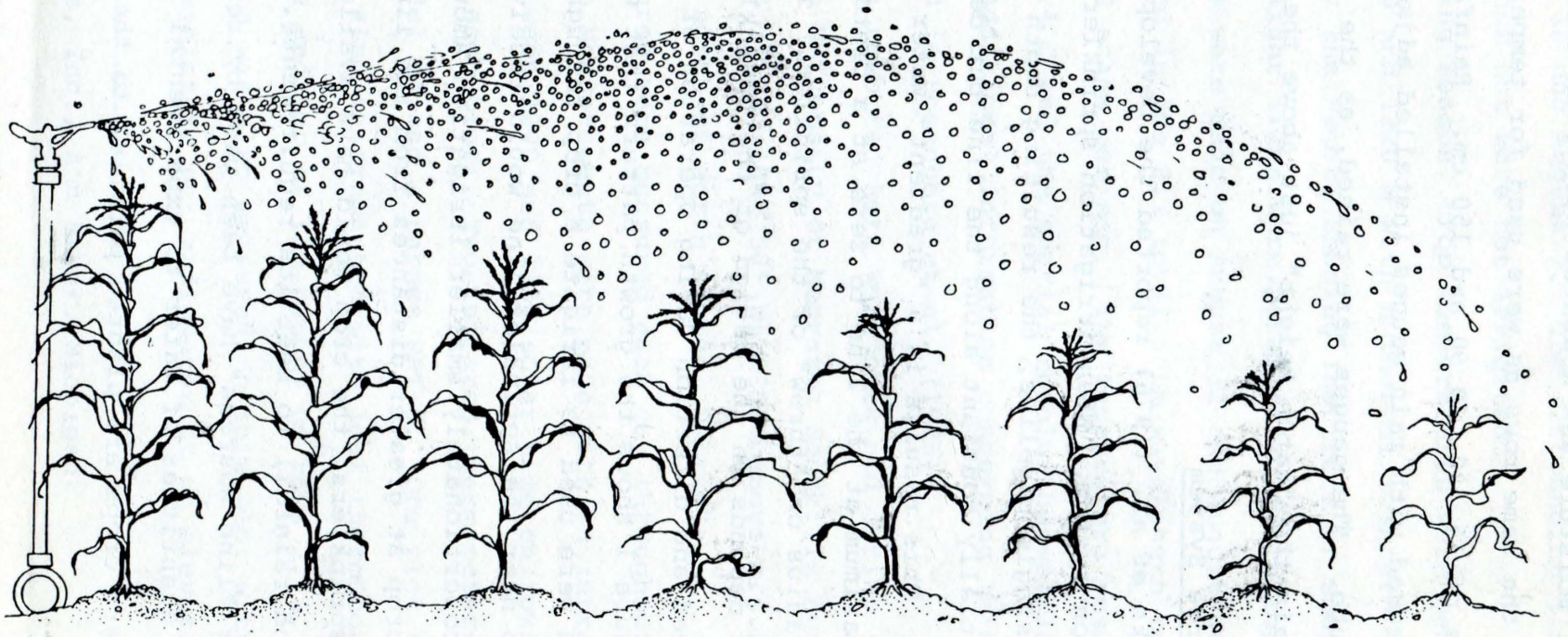


Fig. 1. Sketch showing reduced growth pattern perpendicular to line source system operated on full gradient for the entire growing season.

row becomes, in effect, a different treatment since each row receives a different amount of water than its neighbors to either side. Because of the relatively small differences in applied water betwen neighboring rows, rows can be placed in groups of two, three or four. The group of rows would be considered a single treatment.

Modified Line Source

The irrigation system that we used is a modification of the line source system described above. Two irrigation lines were placed on either side of each plot, as shown in Fig. 2. One line (designated as Full Irrigation) was operated weekly to provide all of the water required by the crop grown in the rows immediately adjacent to it. When the second line (designated as the Treatment Line) was turned off, an irrigation gradient was created across the plot. This is known as a "G" treatment. When both lines are operated, the plot is uniformly irrigated. This is designated as an "I" treatment. Varying levels of stress are created across the plot by imposing a "G" treatment on the plot for designated portions of the growing season. Stress is initiated by switching from an "I" to a "G" treatment and can be terminated by reapplying an "I" treatment.

A sprinkler nozzle and pressure combination was used that provided a nearly linear decrease in the quantity of water that was applied with increasing distance from the sprinkler line. Figure 3 shows the total amount of water applied during the season at various distances from a single-sprinkler line in 1978. There is a nearly linear decrease with distance from the line. During

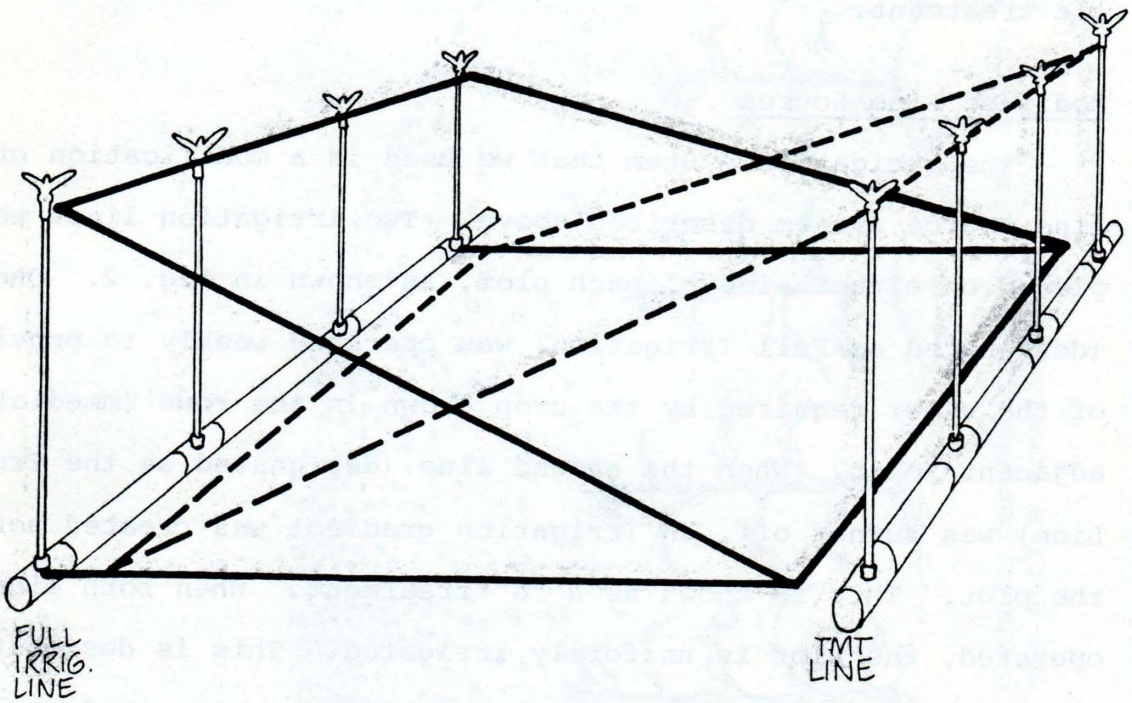


Fig. 2. Schematic of "full" and "treatment" sprinkler lines and the water application pattern resulting from the operation of individual lines. Total water applicatio is the sum of the amounts from the individual patterns

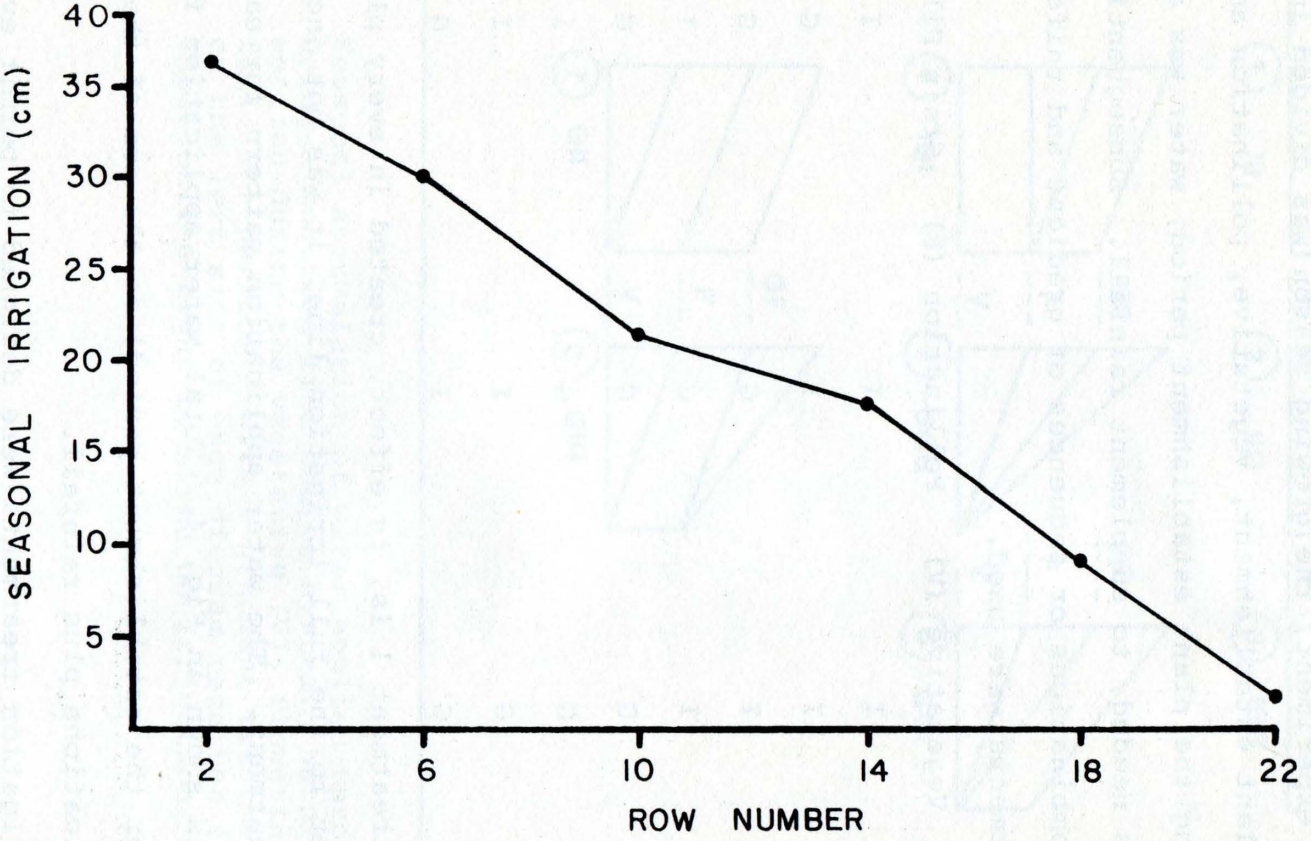


Fig. 3. Accumulated amounts of seasonal irrigation water applied to a G-G-G plot.

any one irrigation, wind effects may cause deviations from the ideal application pattern. However, the sum of two or more irrigations ordinarily compensates for such deviations.

Irrigation Treatments

In our experiment, the growing season was divided into four periods: Plant establishment, vegetative, pollination and grain fill. During the plant establishment period, water was applied uniformly as needed, to supplement rainfall. Subsequently the following combinations or sequences of gradient and uniform irrigation treatments were used.

Treatment	Vegetative (V)	Pollination (F)	Grain Fill (GF)
1.	I	I	I
2.	I	I	G
3.	I	G	G
4.	I	G	I
5.	G	G	G
6.	G	G	I
7.	G	I	I
8.	G	I	G

Since treatment 1 is, in effect, created in every plot in the rows adjacent to the full irrigation line, it was not included as a separate treatment. The water application pattern for each of the treatments is shown in Fig. 4. Total water application for the season (after the establishment period) is the sum of the individual period applications plus rainfall.

The irrigation treatments were designed to permit evaluation of the effects of moisture stress on plant temperature, vegeta-

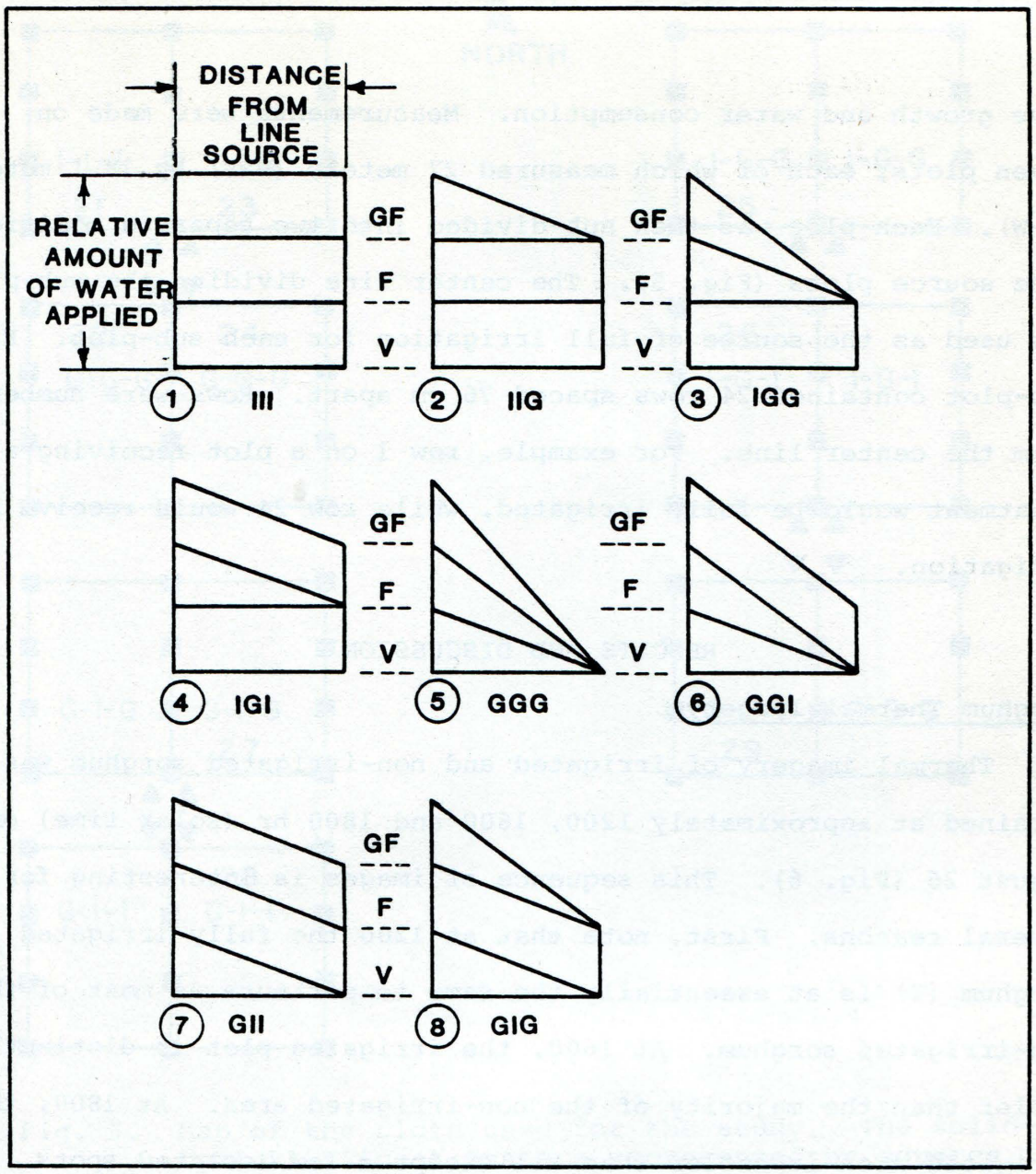


Fig. 4. Seasonal accumulation of water applied through irrigation using a modified line source system. Water treatments were applied during the vegetative (V), flowering (F) and grain-fill (GF) periods. With a gradient treatment (G), plants on the left side of each diagram received full irrigation; those on the right received no irrigation.

tive growth and water consumption. Measurements were made on seven plots, each of which measured 27 meters (N-S) by 19.1 meters (E-W). Each plot was then sub-divided into two separate modified line source plots (Fig. 5). The center line dividing the sub-plots was used as the source of full irrigation for each sub-plot. Each sub-plot contained 24 rows spaced 76 cm apart. Rows were numbered from the center line. For example, row 1 on a plot receiving a G treatment would be fully irrigated, while row 24 would receive no irrigation.

RESULTS AND DISCUSSION

Sorghum Thermal Imagery

Thermal imagery of irrigated and non-irrigated sorghum was obtained at approximately 1200, 1600 and 1800 hr (solar time) on August 26 (Fig. 6). This sequence of images is interesting for several reasons. First, note that at 1200 the fully irrigated sorghum (I) is at essentially the same temperature as most of the non-irrigated sorghum. At 1600, the irrigated plot is distinctly cooler than the majority of the non-irrigated area. At 1800, the irrigated area is cooler than all except a few isolated spots.

Another feature of interest in these images is the temperature pattern of one non-irrigated plot (marked with an N). At 1200, the temperature across this plot were fairly uniform. At 1600 and 1800, however, the temperatures were quite variable on this plot. This indicates that some but not all of the plants in this area had adequate water. Thus, a large temperature variability within a field may signal the presence of soil moisture deficits. Such deficits may occur because of inhomogeneous

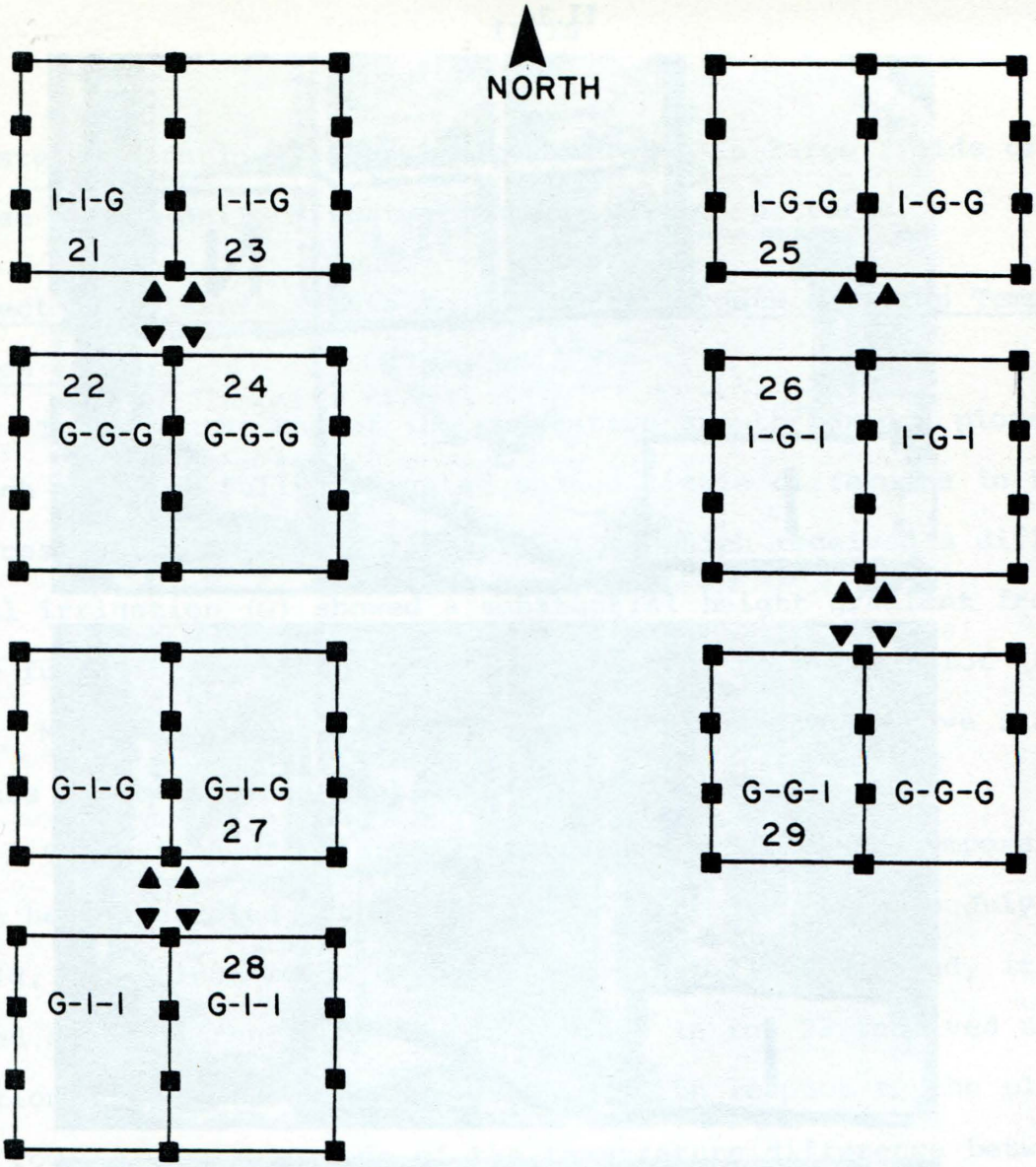


Fig. 5. Map of the plots used for the study. The solid-set sprinkler locations are represented by squares. Row 2 is indicated by the arrows. Plot 22 was instrumented with air and leaf thermocouples. Numbered plots are those on which infrared canopy temperatures were measured.

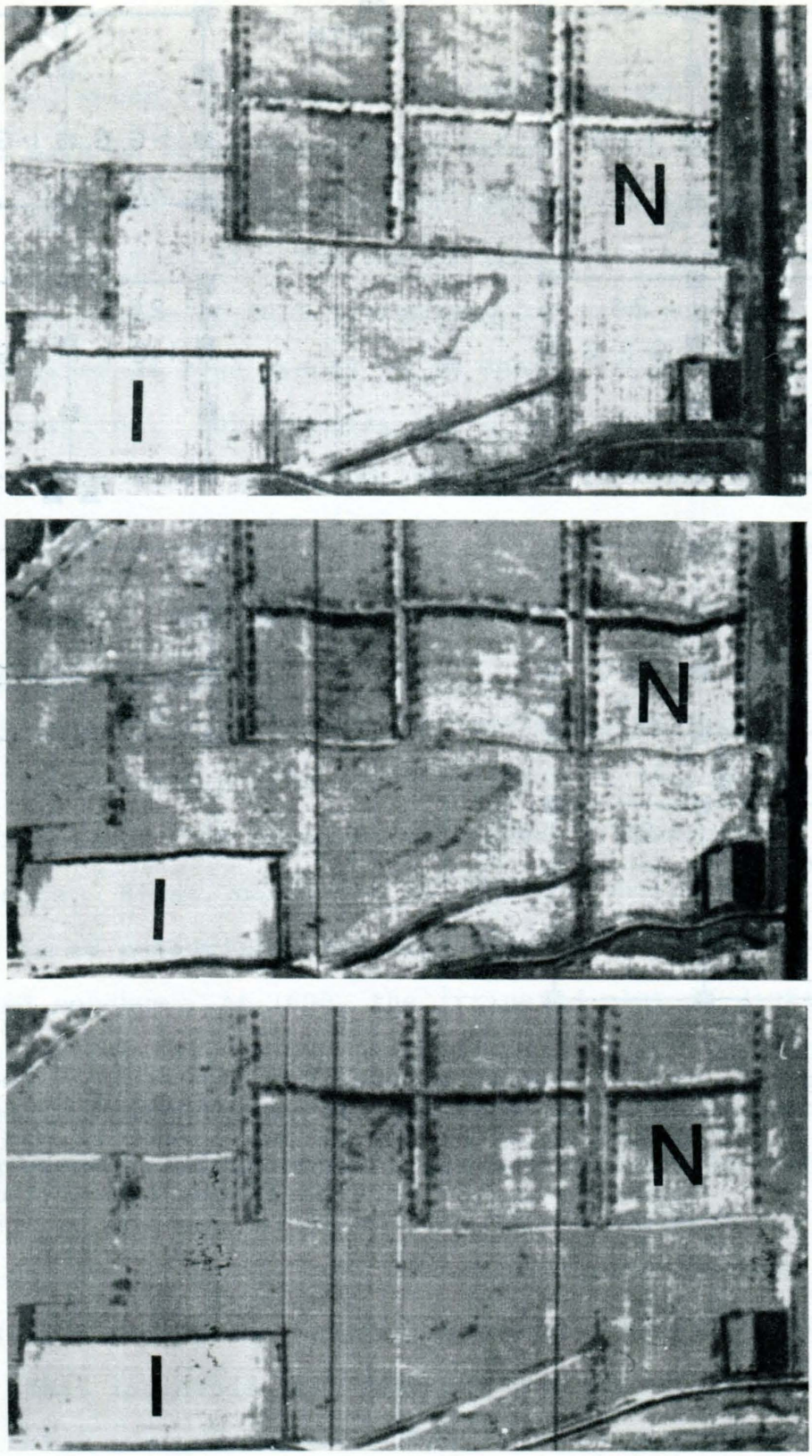


Fig. 6. Thermal imagery of irrigated and non-irrigated sorghum on August 26, 1974, at Mead, Nebraska. An irrigated plot is marked with an I and a non-irrigated plot with an N. The lighter the shade the cooler the temperature. A (1148 h), B (1613 h) and C (1817 h). All remaining areas were planted to non-irrigated sorghum. The lines forming distinctive tic-tac-toe pattern are tree shelter-belts.

moisture retention properties of the soil in large fields or because of non-uniform irrigation application patterns.

Effect of Moisture Stress on Vegetative Growth and Crop Temperatures in Corn

Thus, at the end of the vegetative growth period, plots which had been fully irrigated showed little difference in height across a plot, whereas plants in plots which received a differential irrigation (G) showed a substantial height gradient from the fully irrigated to the non-irrigated side of the plot (Fig. 7). Moisture stress, if prolonged during the vegetative stage, tends to reduce the height of corn plants.

The effect of moisture stress on mid-day plant temperatures can be illustrated with data for the period July 12 to July 18 (Fig. 8). Since row 2 of each plot was fully irrigated, it was used as a reference point. The plants in row 22 received no irrigation and had elevated temperatures with respect to the plants on row 2. The magnitude of the temperature difference between row 22 and row 2 (ΔT_{22}), on a given plot, changed from day to day. This is due to day to day differences in environmental factors which can influence the temperature of a plant.

There is considerable variation in ΔT_{22} between the various plots. That is, some non-irrigated plants had more soil moisture available to them and were cooler than other plants, hence, the variability in the magnitude of stress as suggested by differences in the ΔT_{22} values. The most extreme example of this occurred on July 17, when ΔT_{22} was only 0.8 C in plot 24 but was 12.9 C in plot 27.

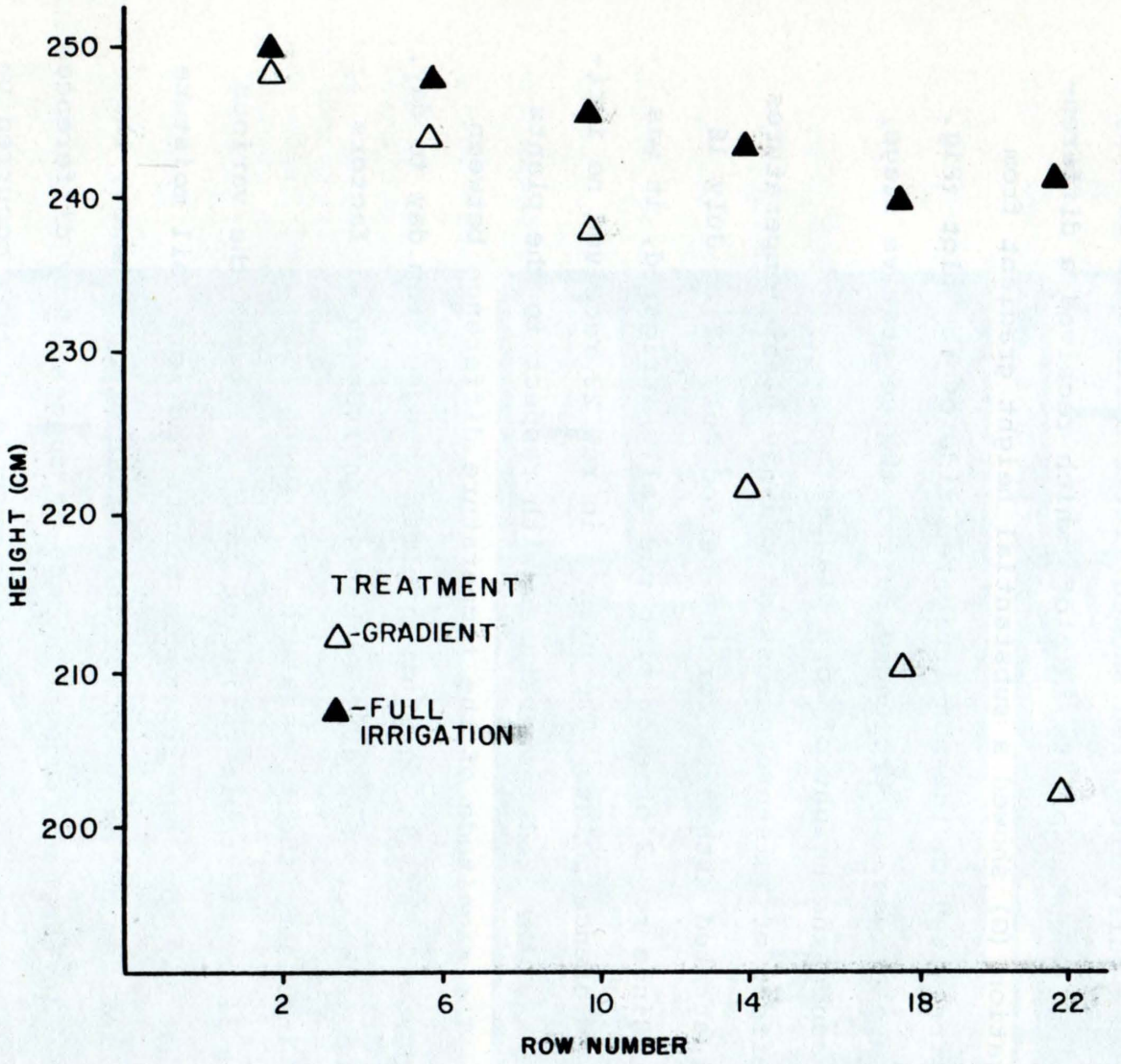


Fig. 7. Average height of corn plants by row. Measurements were made on July 21, 1978, near the end of the vegetative growth period.

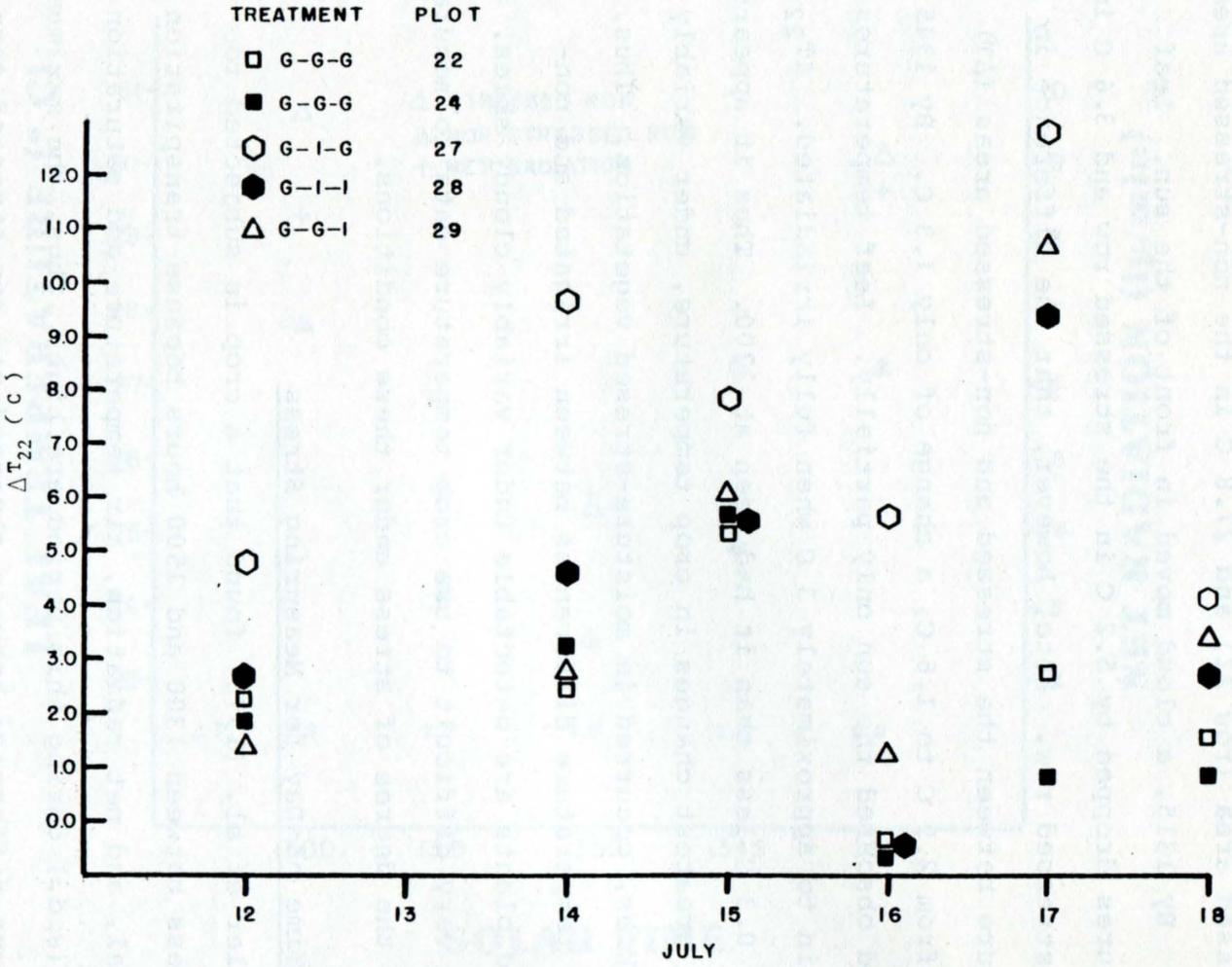


Fig. 8. Elevation in mid-day temperature of row 22 above that of row 2 (ΔT_{22}) for several corn plots. Each plot received a water gradient treatment during the vegetative growth stage. Data are for July 12-18, 1978.

Effect of Variable Cloud Cover on Crop Temperature Measurements

Partly cloudy skies create difficulties in observing crop temperature under field conditions. The effect of a transient cloud on leaf temperature is illustrated in Fig. 9. At 1300, plot 22 was fully irradiated. Leaf temperatures were 30.6 C in the stressed area (row 22) and 27.8 C in the non-stressed area (row 2). By 1315, a cloud moved in front of the sun. Leaf temperatures dropped by 5.2 C in the stressed row and 3.6 C in the non-stressed row. Note, however, that the difference in temperature between the stressed and non-stressed areas (ΔT) dropped from 2.9 C to 1.6 C, a change of only 1.3 C. By 1345 the cloud obscured the sun only partially. Leaf temperatures rose again to approximately 3 C when fully irriadiated. ΔT_{22} was only 0.3 C less than it had been at 1300. Thus it appears that the greatest changes in crop temperature, under variably cloudy skies, occurred in moisture-stresed vegetation. Thus, although temperature differences between irrigated and non-irrigated plants are detectable under variably cloudy skies, it would be very difficult to use crop temperature data to accurately quantify the degree of stress under these conditions.

Optimum Time of Day for Measuring Stress

Ehrler et al. (1978) found that a crop is subjected to high stress between 1300 and 1500 hours because transpiration is maximal, and net radiation, air temperature and saturation deficit (s.d.) during this period are high. Thus, the maximum temperature difference between stressed and non-stressed corn plants (ΔT_{max}) should occur during this period of the day. In

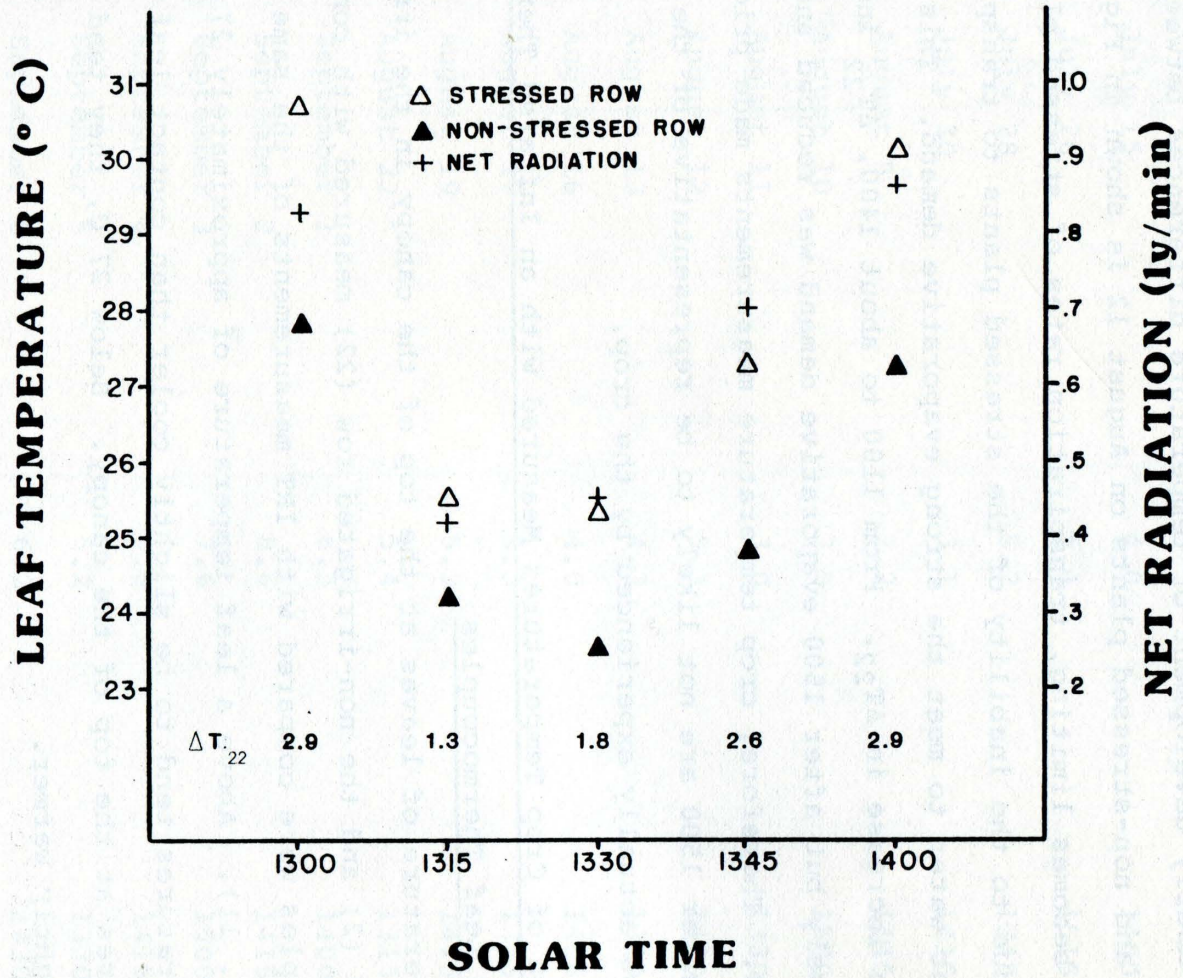


Fig. 9. Thermocouple temperatures of sunlit leaves (level 3) in row 2 (non-stressed) and row 22 (stressed) in plot 22 between 1300 and 1400 on July 7, 1978, a partly cloudy day. ΔT_{22} ($\Delta T_{22} = T_{22} - T_2$) is computed for each observation. Net radiation above row 2 is included to illustrate effects of clouds on the radiation flux density.

order to determine when ΔT_{max} occurs, we analyzed the diurnal leaf temperatures of sunlit leaves in rows 2 and 22 of plot 22 for 21 clear days between June 26 and September 6. In Table 1 it is seen that ΔT_{max} occurred between 1300 and 1500 throughout the season. For this reason we suggest measurement of ΔT_{max} at about 1400 hours.

The hourly development of temperature differences between stressed and non-stressed plants on August 12 is shown in Fig. 10. As water becomes limiting, transpiration rates of stressed plants decline due to the inability of the stressed plants to transpire sufficient water to meet the strong evaporative demand. This causes an increase in ΔT_{22}. From 1100 to about 1400, ΔT_{22} increased continuously but after 1500 evaporative demand was reduced and ΔT_{22} decreased. Therefore, crop temperature measurements made prior to 1300 or after 1500 are not likely to be representative of the maximum stress actually experienced by the crop.

Comparison of Crop Temperatures Measured with an Infrared Thermometer and Leaf Thermocouples

Temperature of leaves at the top of the canopy in the irrigated row (2) and the non-irrigated row (22) measured with contact thermocouples were compared with IRT measurements of the same rows (Fig. 11). Above a leaf temperature of approximately 27 C, IRT temperatures tend to be slightly cooler than contact leaf temperatures at the top of the canopy. Below 27 C, they tend to be slightly warmer.

IRT data represent an integration of the temperature of leaves at the top of the canopy, some leaves within the canopy

Table 1. Time of occurrence of maximal temperature differences (ΔT_{max}).

Date	ΔT_{max} (C)	Time of Day
June 26	5.0	1345
June 27	4.1	1315
July 15	4.0	1400
July 26	5.4	1515
July 28	5.2	1345
July 30	3.1	1415
August 5	2.2	1445
August 10	2.5	1500
August 11	3.0	1330
August 12	5.3	1430
August 13	4.3	1330
August 16	4.0	1400
August 17	5.3	1345
August 19	5.3	1415
August 22	5.4	1315
September 1	6.5	1400
September 2	8.4	1415
September 3	7.6	1500
September 4	9.9	1415
September 5	5.2	1330
September 6	6.2	1430

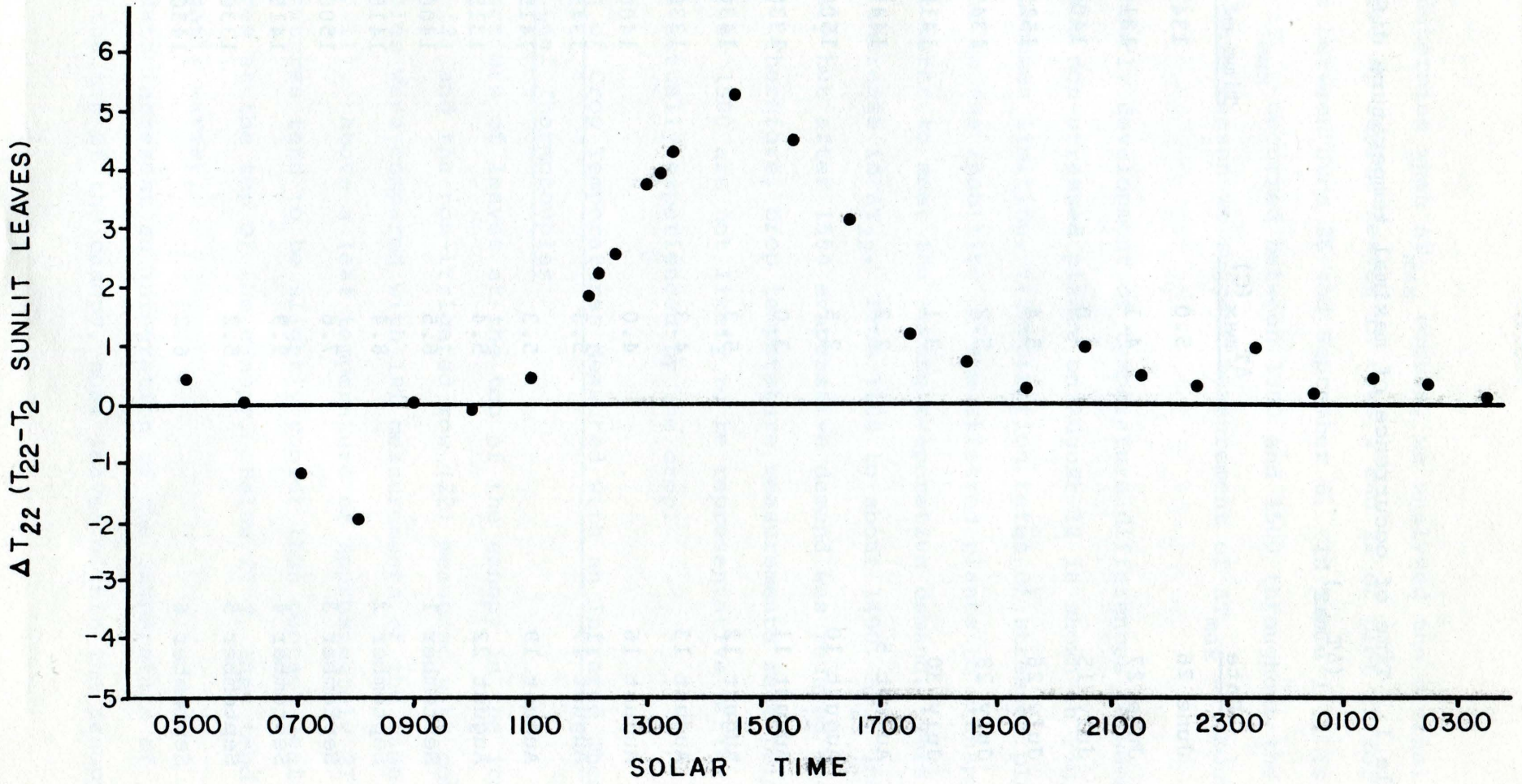


Fig. 10. Typical diurnal pattern of ΔT_{22}.

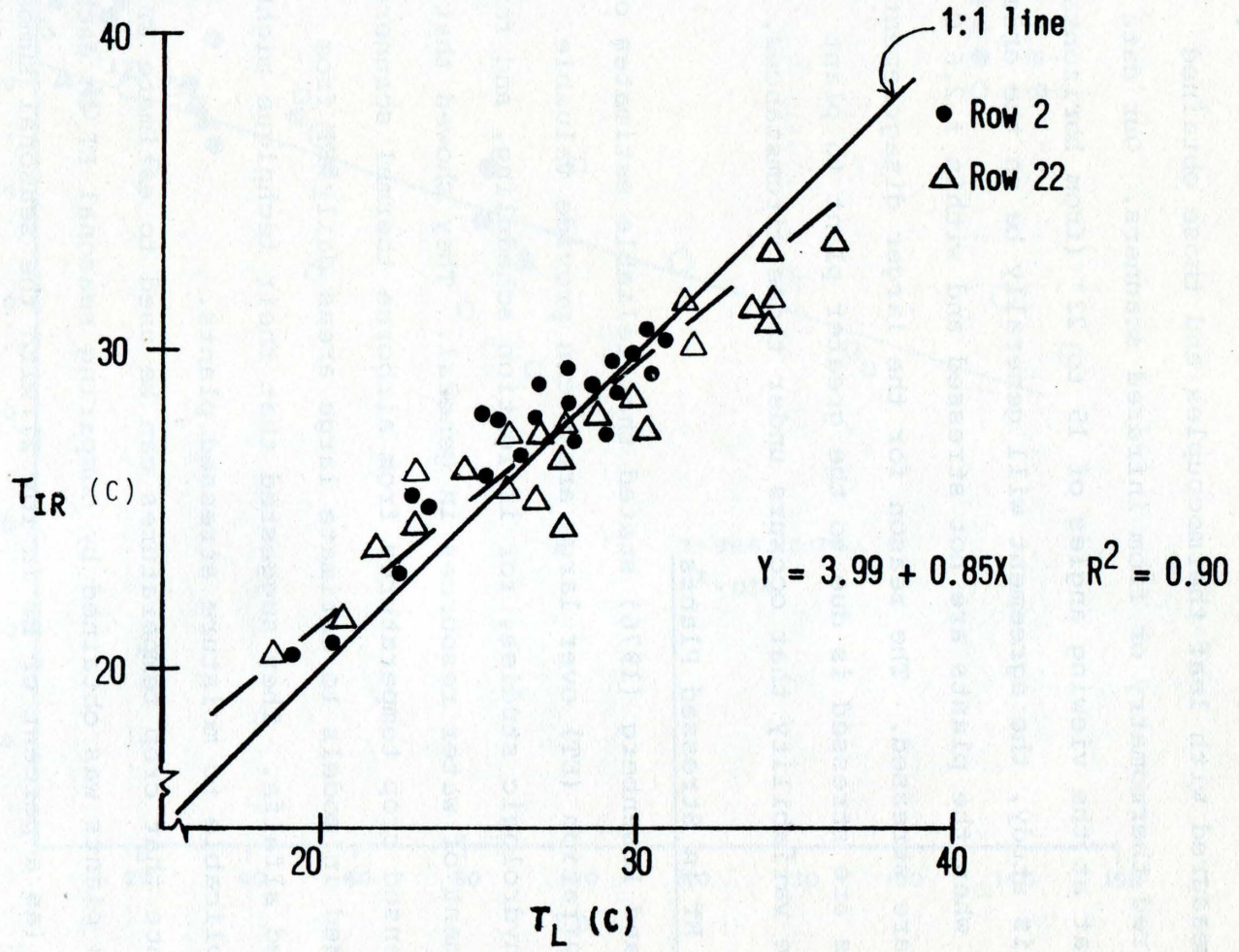


Fig. 11. Mid-day canopy temperatures (T_{IR}) and mid-day leaf temperatures (T_L) at the top of the canopy in row 2 (non-stressed) and row 22 (stressed) of plot 22 on 26 clear days between July 19 and September 6, 1978.

and any exposed soil that is viewed. The depth of view into the canopy of the IRT (or any other thermal scanner) depends on the viewing angle, the type of crop and the amount of crop cover. Thus, exact agreement should not be expected between crop temperatures measured with leaf thermocouples and those obtained from infrared thermometry or from infrared scanners. Our data suggest that at the viewing angles of 15 to 22° (from horizontal) used in this study, the agreement will generally be on the order of ± 1.2 C when the plants are not stressed and within ± 2.6 C when they are stressed. The reason for the larger disagreement when plants are stressed is due to the greater plant to plant temperature variability that occxurs under these circmstances.

Estimating ET in Stressed Plants

Blad and Rosenberg (1976) stated that reliable estimates of evapotranspiration (ET) over large areas can provide valuable input for hydrologic studies, for irrigation scheduling, and for the management of water resources in general. They showed that remotely sensed crop temperatures from airborne thermal scanners could be used in models to estimate large areas daily ET from non-stressed alfalfa. They suggested that their technique might also be applicable to moisture stressed plants.

Evidence that crop temperatures can be used to estimate ET in stressed plants was obtained by comparing seasonal ET on each sample row (as a percent of ET in row 2) with the seasonal summation of ΔT values (Fig. 12). Our data show that these reductions can be estimated to within ± 6% (standard error of estimate) with the use of crop temprature data.

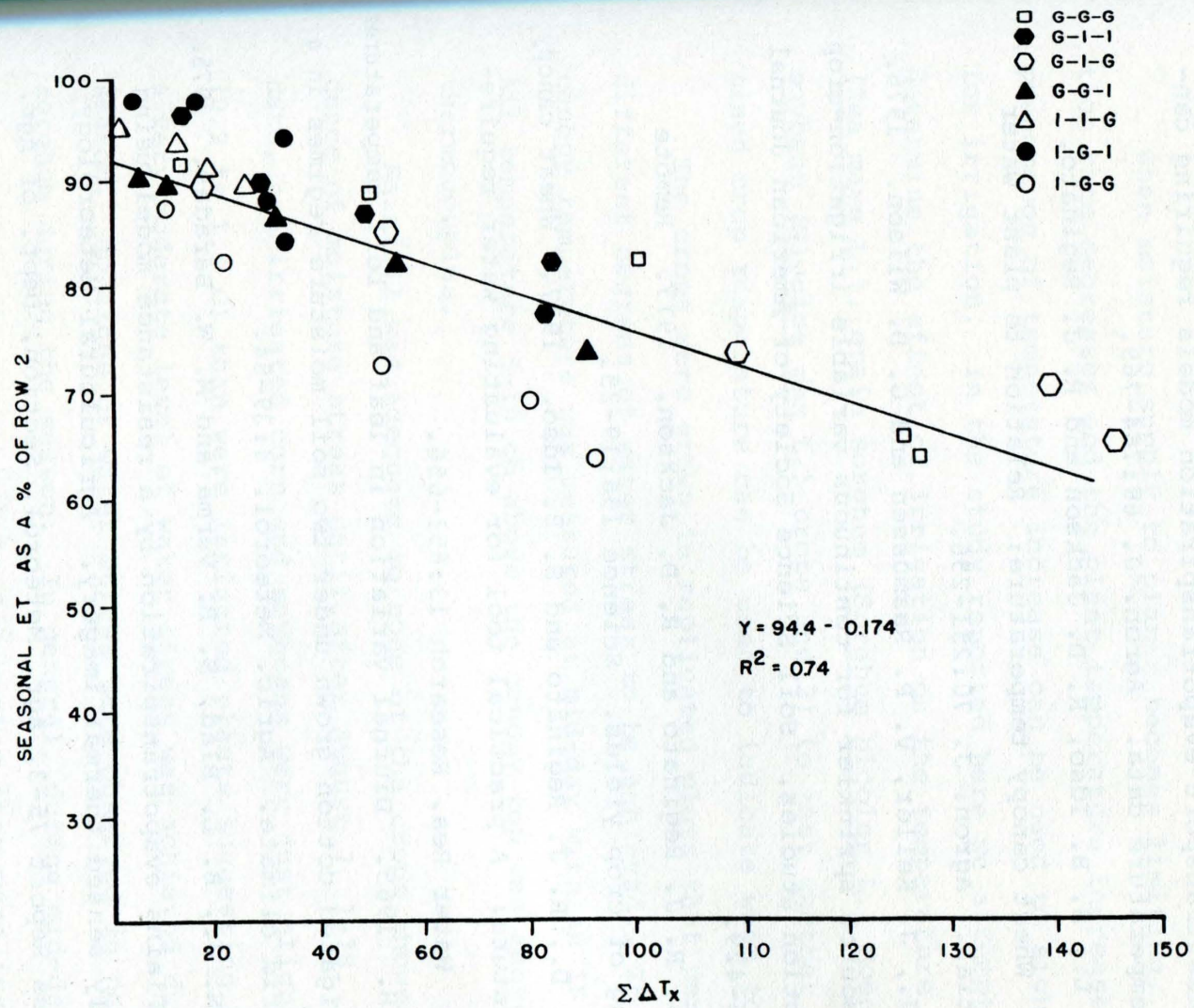


Fig. 12. Seasonal evapotranspiration (ET), expressed as a percent of ET in row 2, as a function of the sum of the difference in mid-day IRT temperature between row x (stressed) and row 2 (non-stressed) ($\Delta T_x = T_x - T_2$), x = 6, 10, 14, 18, 22.

REFERENCES

Bartholic, J. F., L. N. Namken and C. L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and crop canopies differing in water stress. Agron. J. 64:603-608.

Blad, B. L. and N. J. Rosenberg. 1976. Evaluation of resistance and mass transport evapotranspiration models requiring canopy temperature data. Agron. J. 68:764-769.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.

Hanks, R. J., J. Keller, V. P. Rasmussen and G. D. Wilson. 1976. Line source sprinkler for continuous variable irrigation-crop production studies. Soil Science Society of American Journal 40:426-429.

Idso, S. B., R. J. Reginato and R. D. Jackson. 1977. Remote sensing of crop yields. Science 196:19-25.

Jackson, R. D., R. J. Reginato and S. B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Res. Research 13:651-656.

Palmer, J. H. 1965. Diurnal variation in leaf and boll temperatures of irrigated cotton grown under two soil moisture regimes in a semi-arid climate. Agric. Meteorol. 4:39-54.

Rosenberg, N. J., B. L. Blad, S. B. Verma and M. W. Baradas. 1975. Great Plains evapotranspiration by a resistance model using remotely sensed thermal imagery. Agricultural Meteorology Progress Report 75-3, Agr. Meteorol. Section, Dept. of Agr. Engr., Inst. of Agriculture & Natural Resources, Univ. of Nebraska-Lincoln.

Tanner, C. B. 1963. Plant temperatures. Agron. J. 55:210-211.

CHAPTER III

CROP TEMPERATURE OF SORGHUM, CORN AND SOYBEANS AS INFLUENCED BY IRRIGATION TREATMENT

B. L. Blad and K. L. Clawson

ABSTRACT

When moisture supply to plants becomes limiting, transpiration rate decreases and the plant temperature increases. This phenomenon of temperature increase can be used to signal the need for irrigation. In the study reported here we attempted: 1) to determine the effect of irrigation on the temperature of corn (Zea mays L.), grain sorghum (Sorghum bicolor L. Moench) and soybean (Glycine max L.) crops and 2) to test whether a predetermined crop temperature can be used to indicate when to irrigate.

The crops were grown in replicated plots that permitted four different degrees of water stress to be achieved. In each plot canopy temperature was measured at mid-day with an IR thermoemter. Air temperature 5-10 cm above the canopy top was measured with thermocouples.

Rainfall was adequate so none of the crops showed any evidence of moisture stress until after August 7, 1978. After that date, non-irrigated corn and soybeans were just slightly warmer (0.2 to 1.5 C) than were irrigated plants suggesting that only a very moderate level of water stress was achieved during the season. No signs of water stress were observed in non-irrigated sorghum during the season. In general, during mid-day periods, irrigated soybeans were 1 to 3 C cooler than were irrigated corn or sorghum. This suggests that soybeans have a greater transpiration rate or a more effective mechanism for transfering sensible

heat from the plant to the air than do either of the other crops studied.

INTRODUCTION

The crop temperature, T_c, integrates all variables which affect the transpiration rate and the energy transfer between the plant and the ambient air. The plant temperature may signal the occurrence and even the severity of moisture stress (Hiler and Clark, 1971; Clark and Hiler, 1973). Studies have shown that plant temperatures of water stressed plants are higher than those of non-stressed plants (Mayer, 1970; Miller et al., 1971; Karschen and Pinchas, 1971; Bartholic, et al., 1972).

The temperature of vegetation may depend on the particular type of vegetation or crop (Lange, 1959). For example, Heilman et al. (1976) found that soybeans (Glycine max L.) were 2-3 C cooler than sorghum (Sorghum bicolor L. Moench) under similar climatic and moisture conditions. Blad and Rosenberg (1976) observed different temperatures of alfalfa (Medicago sativa L.), wheat (Triticum aestivum L.), corn (Zea mays L.) and pasture under similar climatic conditions.

The temperature difference between the plant and the air may also be of interest as an indicator of plant stress or as a guide to irrigation scheduling. As plant water stress increases, T_c increases relative to air temperature, T_a. Palmer (1967) found that, when amply watered, the temperature of cotton (Gossypium hirsutum L.) was 1 C cooler than T_a. Under non-irrigated conditions the crop was 2 to 4 C warmer than T_a. A similar response for sorghum was reported by Ehler and van Bavel (1967) and van Bavel and

Ehrler (1968). Ehrler (1973) and Ehler et al. (1978) found that the T_c-T_a differences were measurable and predictable and, thus, might be used to schedule irrigations. They did state, however, that T_c-T_a may be a reliable indicator only in sunny climates.

Aston and van Bavel (1972) stated that the onset of soil water deficit can be detected by comparing the canopy temperature of a stressed plot with the temperature of a well-watered plot. Ritchie (1977) suggested the use of the temperature difference between stressed and non-stressed vegetation as a way of detecting soil moisture deficits. Nixon et al. (1973) did caution, however, that using the average canopy temperature elevation of water-stressed plants above non-stressed plants may not be strictly valid because of the temperature variations that occur across a field.

In view of the above we undertook a study, the objectives of which were: 1) to examine the crop temperature responses of corn, grain sorghum and soybeans to different irrigation treatments and 2) to evaluate the use of a predetermined crop temperature level as an indication of when to irrigate.

MATERIALS AND METHODS

The experiment was conducted at the University of Nebraska Agricultural Meteorology Laboratory at Mead (41° 09' N; 96° 30' W; 354 m above MSL). Corn, sorghum and soybeans were planted in 0.5 m rows in 6x20 m plots. Each plot was replicated. Soil in the experimental field at Mead is a Sharpsburg silty clay loam. Four different irrigation treatments were planned but, due to abundant rainfall, only three treatments were possible. These

were: a) well-watered, b) dryland and c) irrigation when the temperature difference between the well-watered plot and the stressed plot reach 1 C. This is called the 1SWW (stressed minus well-watered) treatment.

Because of limitations in the irrigation system it was necessary to irrigate all 1 SMW plots when one of them become 1 C warmer than the coresponding well-watered plot. Crop temperatures were measured daily between 1200 and 1300 hr solar time with a Barnes IT-3 IR thermometer. Measurements were made in each plot from atop a 2 m ladder. Three readings were averaged to give the crop temperature. Air temperature measurements were made 5 to 10 cm above the canopy in four different plots for each of the three crops. Ground squirrel damage and moisture problems in the signal cables and junction boxes, which were not rectified until late in the study, minimized the utility of the air temperature data.

RESULTS AND DISCUSSION

Sorghum crop temperatures are presented in Fig. 1. There was no evidence of water stress in any of the sorghum plots during 1978. Temperatures of the well-watered sorghum plot were never consistently cooler than that of the plot that received no supplemental irrigation. Irrigation of the 1SMW plot on August 15 caused no detectable cooling of that plot relative to the dryland plot. The 1SMW and the dryland plot had received the same amount of water prior to that date. The evidence is, therefore, rather conclusive that, in 1978, natural rainfall and stored soil moisture were adequate to prevent any water

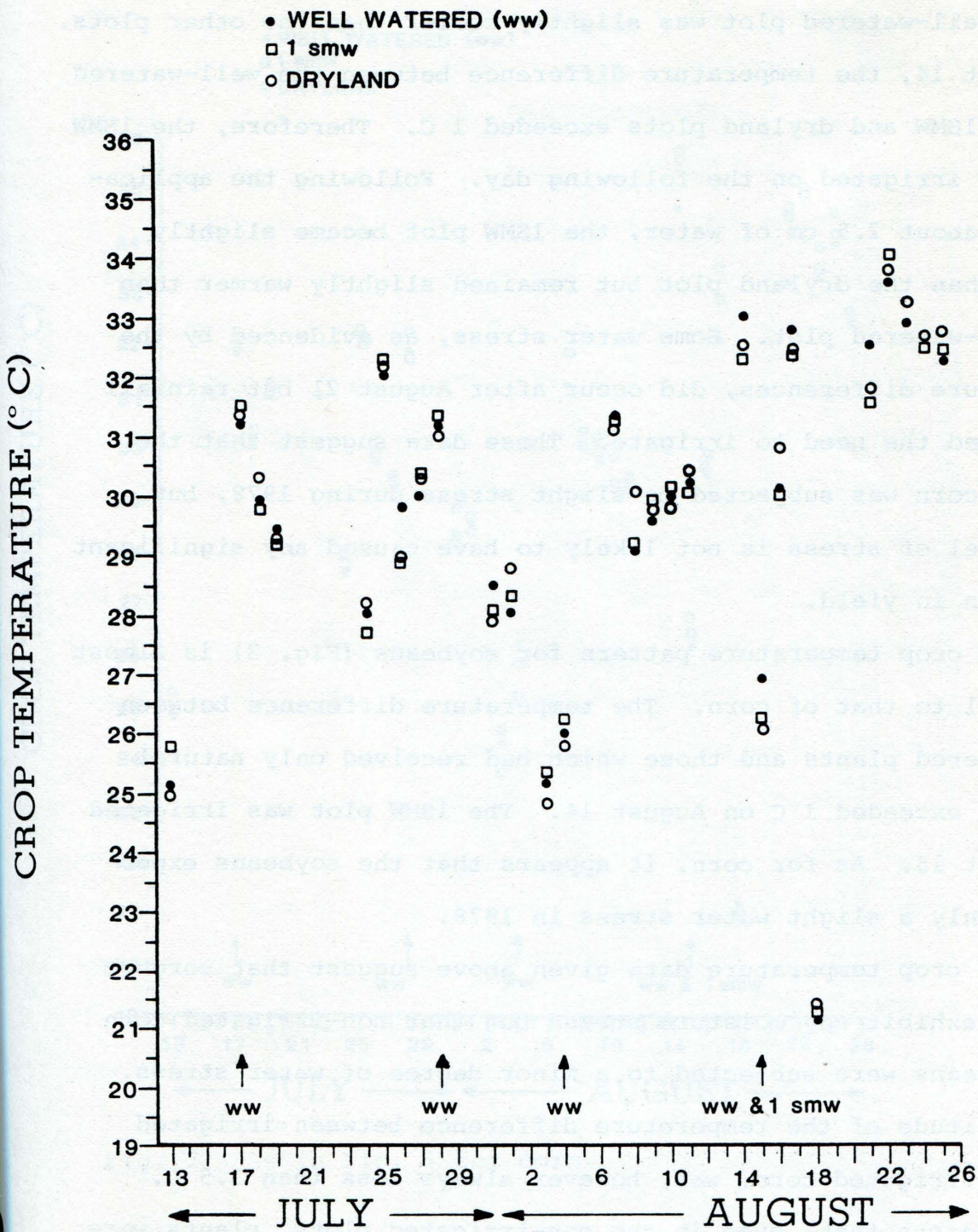


Fig. 1. Crop temperatures measured with an infrared thermometer for sorghum receiving different irrigation treatments. Dates of irrigation are indicated by the arrows. Data were obtained July 13 through August 25, 1978, at the University of Nebraska Mead Field Laboratory.

stress in sorghum at Mead.

There was no tendency before August 7 for the well-watered corn to be cooler than in the other plots (Fig. 2). After August 7, the well-watered plot was slightly cooler than the other plots. By August 14, the temperature difference between the well-watered and the 1SMW and dryland plots exceeded 1 C. Therefore, the 1SMW plot was irrigated on the following day. Following the application of about 2.5 cm of water, the 1SMW plot became slightly cooler than the dryland plot but remained slightly warmer than the well-watered plot. Some water stress, as evidenced by the temperature differences, did occur after August 21 but rainfall eliminated the need to irrigate. These data suggest that the dryland corn was subjected to slight stress during 1978, but this level of stress is not likely to have caused any significant reduction in yield.

The crop temperature pattern for soybeans (Fig. 3) is almost identical to that of corn. The temperature difference between well-watered plants and those which had received only natural rainfall exceeded 1 C on August 14. The 1SMW plot was irrigated on August 15. As for corn, it appears that the soybeans experienced only a slight water stress in 1978.

The crop temperature data given above suggest that sorghum did not exhibit any moisture stress but that non-irrigated corn and soybeans were subjected to a minor degree of water stress. The magnitude of the temperature difference between irrigated and non-irrigated corn, was, however always less than 1.5 C. This suggests that, even in the non-irrigated plots, plants were stressed only slightly. This degree of stress did not greatly

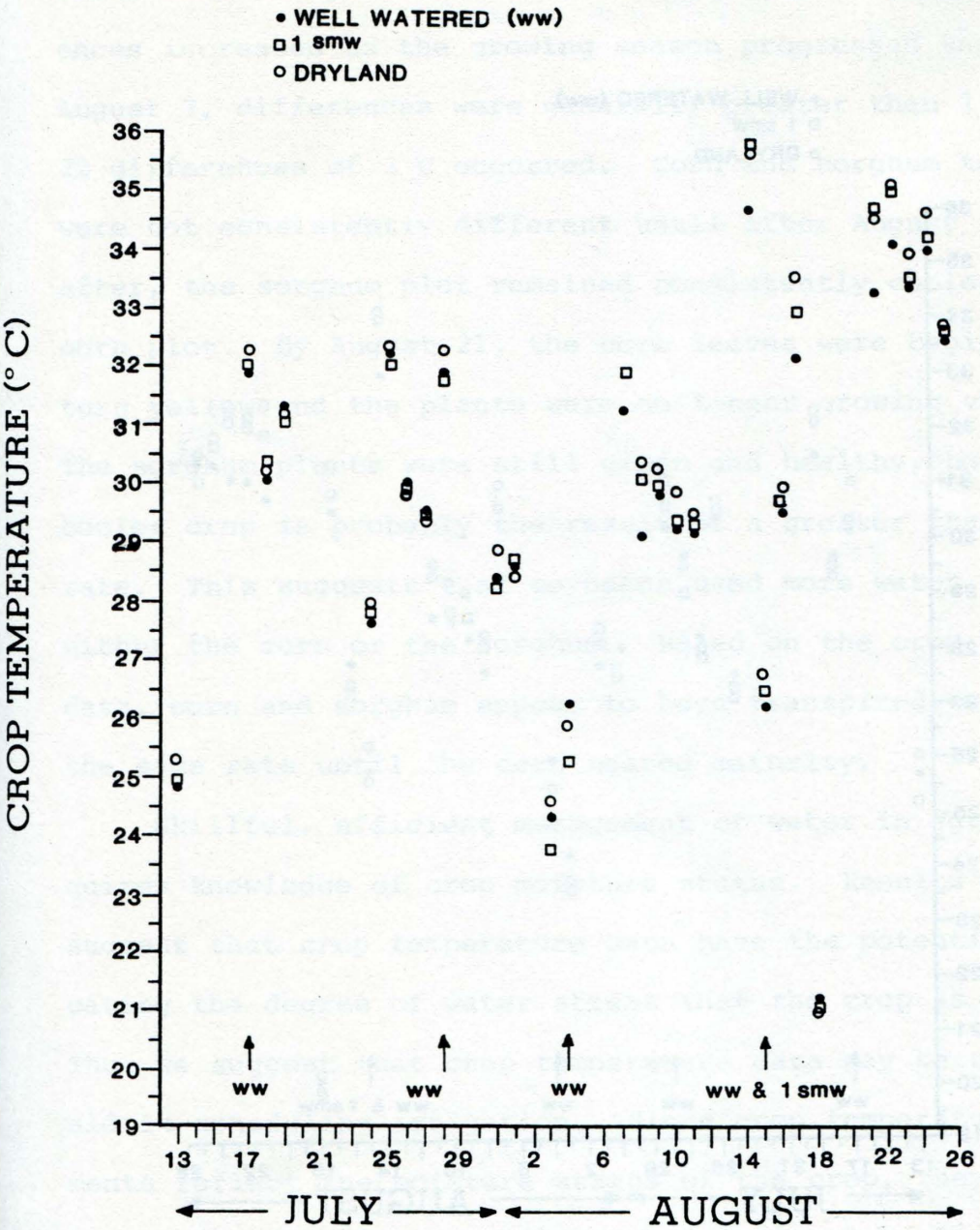


Fig. 2. As in Fig. 1 for corn.

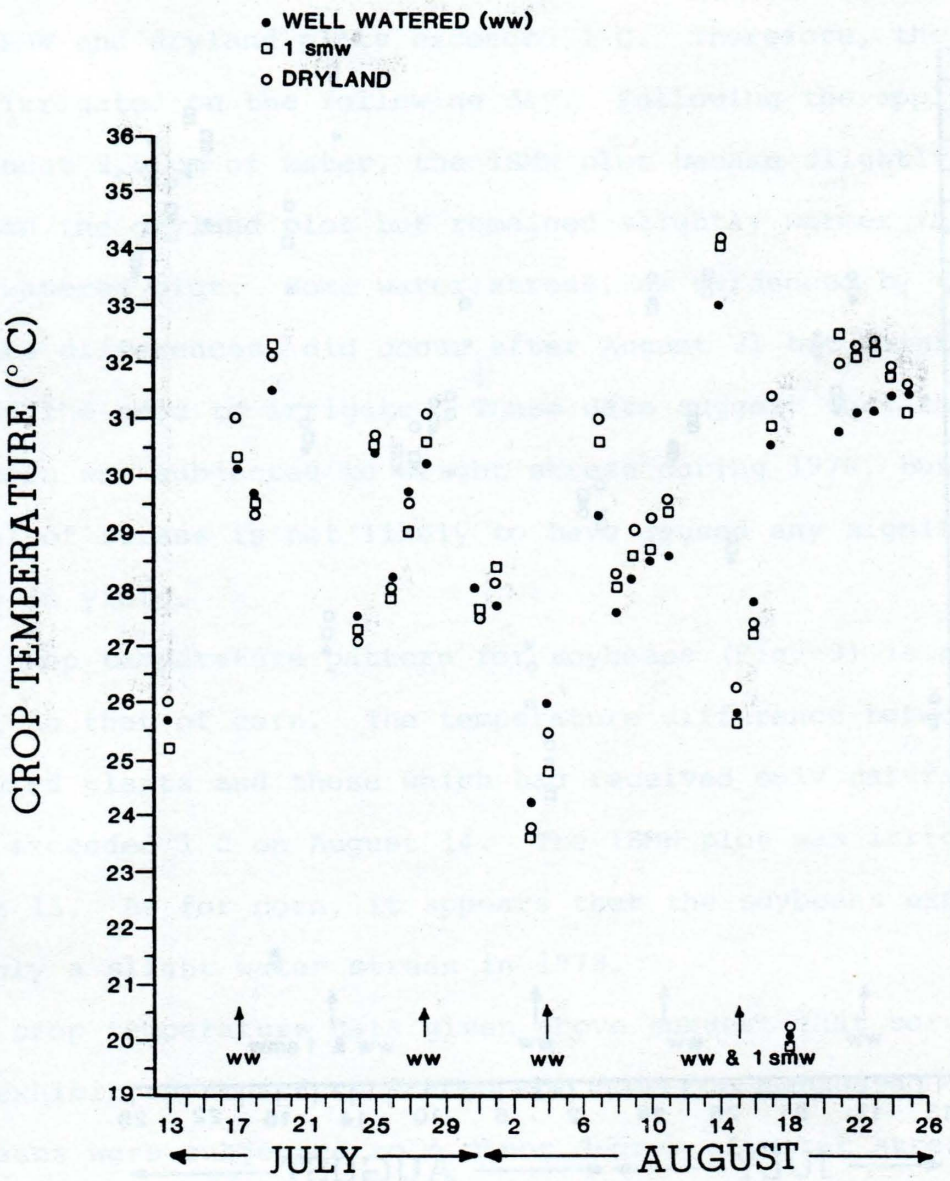


Fig. 3. As in Fig. 1 for soybeans.

reduce yields in the non-irrigated plots.

Crop temperatures of the fully-irrigated corn, sorghum and soybean plots are presented in Fig. 4. After July 24, the soybeans were always cooler than the corn and sorghum. The differences increased as the growing season progressed and, after August 7, differences were generally greater than 1 C. On August 22 differences of 3 C occurred. Corn and sorghum temperatures were not consistently different until after August 21. Thereafter, the sorghum plot remained consistently cooler than the corn plot. By August 21, the corn leaves were beginning to turn yellow and the plants were no longer growing vigorously. The sorghum plants were still green and healthy, however. A cooler crop is probably the result of a greater transpiration rate. This suggests that soybeans used more water than did either the corn or the sorghum. Based on the crop temperature data, corn and sorghum appear to have transpired water at about the same rate until the corn neared maturity.

Skillful, efficient management of water in agriculture requires knowledge of crop moisture status. Results of this study suggest that crop temperature data have the potential for indicating the degree of water stress that the crop is experiencing. Thus we suggest that crop temperature data may be used as an aid in scheduling irrigation. Since crop temperature measurements reflect the moisture status of the crop, they may provide a tool for drought surveillance and monitoring.

The results of this study show that various crops respond differently in their temperature response to moisture stress. Thus, it is unlikely that a general relationship between soil

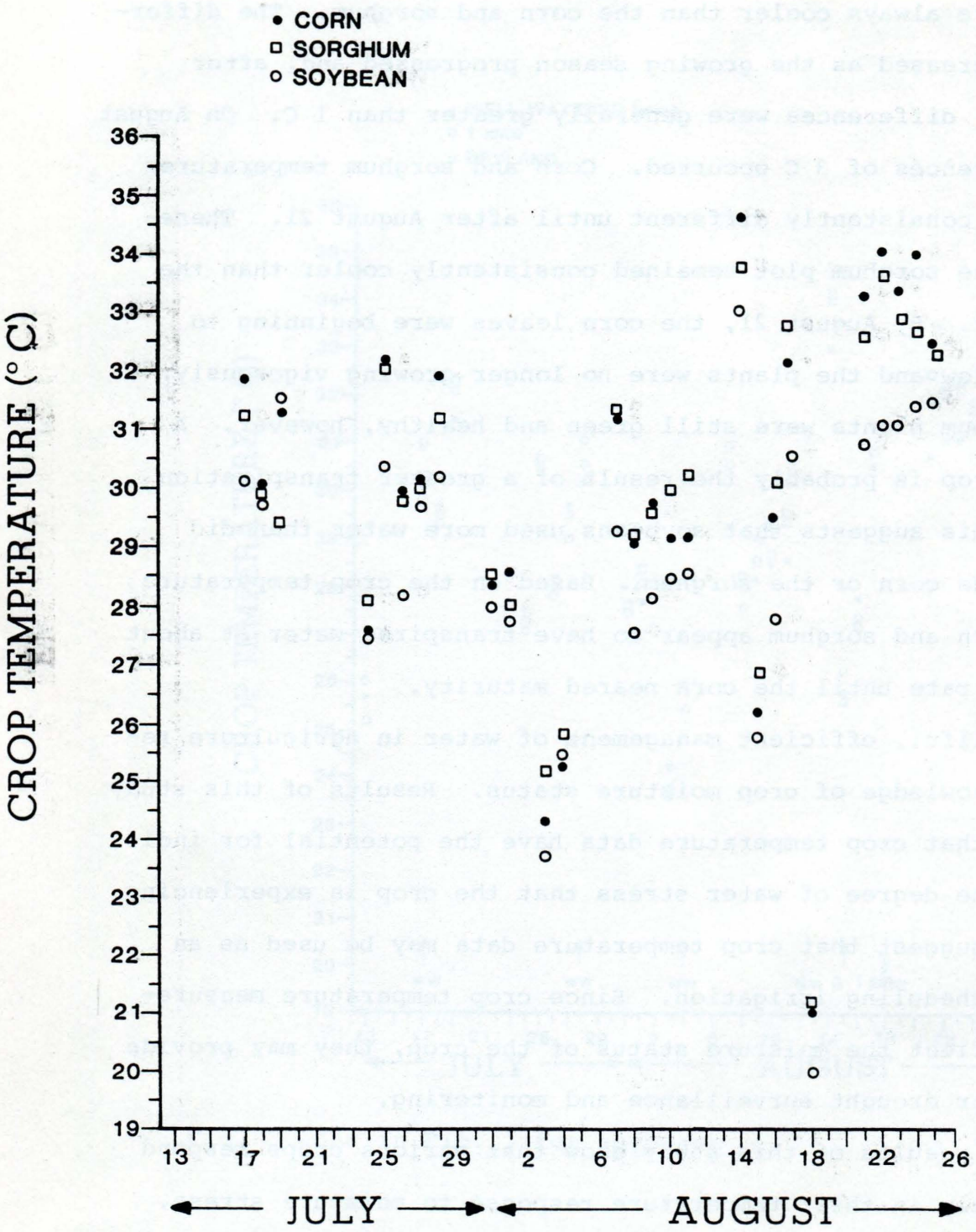


Fig. 4. Crop temperature patterns for the well-watered corn, sorghum and soybean plots during July 12 to August 25, 1980.

moisture and crop temperature can be applied to all agricultural crops but, rather, that the relationship for each crop must be studied separately. When such relationships are established crop temperature measurements may become a valuable aid in water resource management.

REFERENCES

Aston, A. R. and C. H. M. van Bavel. 1972. Soil surface depletion and leaf temperature. Agron J. 64:368-373.

Bartholic, J. F., L. N. Namken and C. L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and crop canopies differing in water stress. Agron. J. 64:603-608.

Blad, B. L. and N. J. Rosenberg. 1976. Measurement of crop canopy temperature by leaf thermocouple, infra-red thermometry and remotely sensed thermal imagery. Agron. J. 68:635-644.

Clark, R. N. and E. A. Hiler. 1973. Plant measurements as indicators of crop water deficits. Crop Sci. 13:466-469.

Ehrler, W. L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J. 65: 404-409.

Ehrler, W. L. and C. H. M. van Bavel. 1967. Sorghum foliar responses to changes in soil water content. Agron. J. 39: 243-246.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978. Diurnal changes in plant water potential and canopy temperatures as affected by drought. Agron. J. 70:998-1004.

Heilman, J. L., E. T. Kanemasu, N. J. Rosenberg and B. L. Blad. 1976. Thermal scanner measurement of crop temperatures to estimate evapotranspiration. Remote Sensing of Environment 5:137-145.

Hiler, E. A. and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Trans. of ASAE 14:757-761.

Karschon, R. and L. Pinchas. 1971. The effect of air temperature and moisture stress upon leaf surface temperatures of Calotropis Procera (Willd.) R. Br. Ecol. Plant. 6:43-50.

Lange, O. L. 1959. Untersuchungen uber warmehaushalt und hitzeresistenz mauretanischer wusten-und savannenpflanzen. Flora 147:595-651.

Meyer, V. I. 1970. Soil, water and plant relations. In Remote Sensing with Special Reference to Agriculture and Forestry. Nat'l Acad. Sci., Washington, D.C., pp. 251-297.

Millar, A. A., R. E. Jensen, A. Bauer and E. B. Norum. 1971. Influence of atmospheric and soil environmental parameters on the diurnal fluctuations of leaf water status of barley. Agr. Meteorol. 9:93-105.

Nixon, P. R., L. A. Namken and C. L. Wiegand. 1973. Spatial and temporal variations of crop canopy temperatures and implications for irrigation scheduling. Proc. Conf. on Earth Resources Observation and Information Analysis System. Remote Sensing of Earth Resources. Vol. II. F. Shahrokhi (ed.) Uni. of Tenn. Tullahoma, Tenn. pp. 643-657.

Palmer, J. H. 1967. Diurnal variation in leaf and boll temperature of irrigated cotton grown under two soil moisture regimes in a semi-aird climate. Agr. Meteorol. 4:39-54.

Ritchie, J. T. 1977. The contribution of the surface energy balance in climatic stress for agriculture. Presented at Climate-Technology Seminar, Oct. 25-26, Columbia, Missouri, 23 pps.

van Bavel, C. H. M. and W. L. Ehrler. 1968. Water loss from a sorghum field and stomatal control. Agron. J. 60:84-86.

CHAPTER IV

RELATIONSHIP BETWEEN CROP TEMPERATURE AND THE PHYSIOLOGICAL AND PHENOLOGICAL DEVELOPMENT OF DIFFERENTIALLLY IRRIGATED CORN

B. R. Gardner, B. L. Blad, R. E. Maurer, D. G. Watts

ABSTRACT

Quantitative data relating crop temperature under different water stress conditions to the phenological and physiological development of corn over a growing season are lacking. This study was motivated by the need to obtain quantitative information which can be beneficially utilized by those who are involved in predicting crop yields and assist those who assess the economic impact of drought on crop production.

Infrared canopy temperatures and physiological and phenological measurements were made in differentially irrigated corn (Zea mays L.) throughout the 1978 growing season. Irrigation treatments were designed to evaluate the effects of moisture stress on these measurements. The soil type in the experiment area is Valentine fine sand (Typic Ustipsamment).

The effect of moisture stress on vegetative growth was demonstrated by an average height difference of 50 cm between fully irrigated and non-irrigated plants.

There was a tendency for plants which had been subjected to moisture stress during the grainfilling stage to mature faster than plants fully irrigated during that period.

Yield reductions were greatest when stress occurred during the pollination or grain-filling periods. Canopy temperature increases between the onset of tasseling and the end of grain-fill

were related to reduced yields.

Five crop temperature indices were tested for their relationship to phenological stage of growth. Three were highly correlated, one had a low correlation and one was not correlated with phenological development.

INTRODUCTION

Hsiao (1973) has summarized the observed plant responses to water stress, which include reductions in the transpiration rate CO_2 assimilation rate, leaf cell size, plant-water potential, growth rate and stomatal aperature. Glover (1959) concluded that evaluation of stomatal response to moisture stress requires a knowledge of the moisture history of the plant. Clark (1973) concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution, and other plant characteristics. Thus, for a true measurement of plant moisture deficit, measurements should be made on the plant instead of the soil or atmosphere.

The effect of moisture stress on vegetative growth and grain yields in corn depends on the degree of stress and on the stage of growth at which stress occurs (Somerhalder, 1962; Sionit and Kramer, 1977). Denmead and Shaw (1960) observed that stress in corn during silking was more harmful to grain yields than stress during any other growth stage.

Reicosky et al. (1975) theorized that a physiological change occurs in corn during pollination which makes the interpretation of leaf water potential measurements after that stage difficult, whereas leaf water potential measurements during the vegetative

period were related to stress.

Ehrler (1973) stated that long-term leaf temperature measurements are an indirect indication of stomatal behavior. Ehrler et al. (1978) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperatures between stressed and non-stressed wheat plants were shown to be a reliable indicator of plant moisture stress.

Quantitative data relating crop temperature under various water stress conditions to the phenological and physiological development of crops over a complete growing season are sparse. The only seasonal crop temperature studies reported thus far are those of Idso et al. (1977) and Jackson et al. (1977) with durum wheat. They showed that an accumulation of crop temperatures during the period between head emergence and the cessation of head growth were related to final grain yields.

The lack of quantitative information in relating canopy temperature to the development of corn (Zea mays L.) motivated the study reported here. The specific objectives of the research were: (1) to evaluate the effectiveness of five crop temperature indices in estimating phenological growth stage and (2) to use information on canopy temperature to estimate reduction in grain yield due to moisture stress.

MATERIALS AND METHODS

Experimental Site

This study was conducted at the University of Nebraska Sandhills Agricultural Laboratory, located near Tryon, Nebraska

(41° 37' N; 100° 50' W; 975 m above sea level). The combination of low rainfall during the growing season, sandy soil (Valentine fine sand - Typic Ustipsamment) and high evaporative demand makes it possible to study the effects of moisture stress at this location without the use of rainout shelters.

Measurements were conducted on nine plots of corn (Zea mays L., cv. Pioneer 3780), each of which measured 27 meters (N to S) by 9 meters (E to W). Each plot contained 24 rows, each 76 cm wide. Along the east and west border of each plot was a solid set sprinkler irrigation system similar in design to that of Hanks et al. (1976). The system which permits the application of water in a gradient across a plot is described in detail in Chapter II.

Irrigation Treatments

Seven different irrigation treatments were employed in this study (Table 1). Each treatment was replicated twice. The full irrigation treatment (I) consisted of restoring 100% of the water used in evapotranspiration to all rows in a plot. The amount of water evapotranspired was determined by measuring soil moisture depletion with a neutron probe. The gradient treatment (G) consisted of applying full irrigation to row 1 of a plot and applying progressively less moisture to each succeeding row, until rows 22 through 24 received essentially no irrigation.

Irrigations were timed to coincide with each of three growth periods: vegetative growth, pollination and grain-filling. The vegetative stage treatments began on June 10, the pollination stage treatments on July 18, and the grain-filling stage treatments on August 12.

Table 1. The seven irrigation treatments used for the study. I means that all rows in a plot received a full irrigation during that growth period. G means that an irrigation gradient was established so that one side of the plots received 100% of its water needs, while no replacement of water was made to the opposite side.

Treatment	Growth Stage		
	Vegetative	Pollination	Grain Filling
1	G	I	I
2	I	G	I
3	I	I	G
4	G	I	G
5	I	G	G
6	G	G	G
7	G	G	I

Soil Plant and Air Measurements

Phenological measurements using the system of Hanway (1966) were made for all moisture treatments at least once each week throughout the growing season. Each plant height and phenological stage observation was made on at least 10 individual plant samples.

Canopy temperatures were measured with an infrared thermometer (IRT) each day between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 of each plot. Readings began on June 1 and continued throughout the growing season, except for a few days when measurement was not possible. Two infrared thermometers were used. A Telatemp model 44 was used between June 13 and July 17. A Barnes model PRT5 was used the remainder of the season. True canopy temperature was calculated from the following expression:

$$T_c = \frac{(\sigma T_{IR}^4 - (1 - \varepsilon_c)B^*)^{\frac{1}{4}}}{\varepsilon_c \sigma}$$

where T_c is the true canopy temperature (°K), T_{IR} is the apparent canopy temperature sensed by the IR thermometer (°K), σ is the Stefan-Boltzman constant, ε_c is the crop emissivity and B* is the incoming longwave radiation. Estimates of B* were obtained at least twice during mid-day, using the aluminum plate apparatus described by Blad and Rosenberg (1976). The aluminum plate was repainted weekly.

Three techniques for measuring infrared canopy temperatures of a particular row were employed. The direct method consisted of placing the IRT next to the upper leaves of a plant. The average of four direct readings was used to represent the canopy

temperature of a given row. The direct method was especially useful during the early part of the growing season when the plants were so small that, if viewed from a distance, bare soil influenced the IRT temperatures so strongly that temperature differences between plants were entirely masked. The direct method was used from June 14 to June 28. Prior to June 14, the plants were so small that they did not entirely cover the area viewed by the IRT. Thermocouple temperatures of sunlit leaves were used as an estimate of canopy temperatures prior to June 14.

The method used from June 29 through July 7 consisted of standing directly in line with a row and viewing an area 5 meters away. Though crop cover was not complete during this period, and differences in crop cover existed between irrigated and nonirrigated rows, the small spot size (less than 25 cm in diameter) of the IRT allowed it to view, essentially, only the canopy.

The third technique, used from July 8 to the end of the study, consisted of viewing the canopy temperature from atop a 3 meter aluminum ladder which was positioned in line with row 14. The maximum width of the IRT spot size was 95 cm; the maximum length was 200 cm. Thus, these IRT measurements integrated the temperature of several plants, primarily those along a single row.

Detailed measurements of leaf temperature profiles were made in one plot. Leaf temperatures were measured throughout the season at 3 different levels (bottom, middle and top) within this plot in rows 2, 6, 10, 14, 18 and 22.

Leaf temperatures at a given level were measured with

evanohm-constantan thermocouples using the method of Steinmetz (1977). Beginning on June 23, leaf temperatures were recorded at least hourly with a Campbell CR5 data logging system. Prior to June 23, leaf temperatures were measured with a hand-held thermocouple meter.

Crop Temperature Indices for Estimating Crop Growth Stage

Five crop temperature indices were evaluated to determine how well they would estimate crop growth stage. These are given in Table 2. Index 1 is the sum of the mid-day canopy temperature. Index 2 is commonly reported in the literature to indicate whether or not a crop is experiencing moisture stress. Jackson et al. (1977) assumed that a crop experiences moisture stress only when index 2 is positive. Index 3 assumes that crop moisture stress occurs whenever positive values are observed; it also requires that a nonstressed area be available for comparing canopy temperatures. Index 4 is similar to a moisture stress index reported by Idso et al. (1977). Index 5 is analogous to the growing degree day. All indices were calculated daily throughout the growing season.

RESULTS AND DISCUSSION

Plant Height

Plants in plots which were fully irrigated during the vegetative period showed little difference in height across the plot. Those in plots which received a differential irrigation treatment showed a substantial reduction in height from the fully-irrigated to the non-irrigated side of the plot. The greatest difference in average plant height among the fully

Table 2. The five crop temperature indices used to estimate crop growth stage. Each index was summed on a daily basis. T_x is the mid-day canopy temperature of row 2, 6, 10, 14, 18 or 22 in a given plot. T_a is the mid-day air temperature 3 meters above the soil surface. T_{min} is the minimum leaf temperature.

$$\text{Index 1} = \Sigma\ T_x$$

$$\text{Index 2} = \Sigma(T_x - T_a)$$

$$\text{Index 3} = \Sigma(T_x - T_2)$$

$$\text{Index 4} = \Sigma(T_x - T_{min})$$

$$\text{Index 5} = \Sigma\left(\frac{T_x + T_{min}}{2} - 10\right)$$

irrigated plants was 15.9 cm while differences between the fully irrigated and non-irrigated plants on the gradient plots were as great as 50.1 cm.

Moisture and temperature stress resulted in measurable differences in plant height between June 10, when the first gradient treatment was applied, and June 19. There was no significant difference in height between irrigated and non-irrigated plants between June 10 and June 13. June 14 and 15 were hot, cloudless days and produced a visible gradient in wilting across the plot. Plants in the fully irrigated rows were slightly wilted while those in the non-irrigated rows were severely wilted. *T, the difference in mid-day temperature between stressed and non-stressed sunlit leaves was 3.0 C on the 14th and 3.6 C on the 15th. On June 16, irrigated plants were 3 cm taller than were non-irrigated plants. By June 19, well-watered plants were 8-14 cm taller than the non-irrigated ones.

Phenological Development

Phenological differences were not observed among the various moisture treatments until after stage 8, when plants were approaching maturity. During the latter stages of the grain-filling period there was a trend for water stressed plants to mature faster than unstressed plants. By September 13, the stressed plants were 0.5 to 0.7 of a growth stage ahead of the well watered ones. Maturity differences are expected since physiological maturity cannot occur until the plants have dried sufficiently. Hence, moisture stressed plants can be expected to dry and mature slightly sooner than do non-stressed plants.

Crop temperature indices 1, 4 and 5 were highly correlated (R^2 = 0.98) with phenological stage of development (Fig. 1). Any one of these indices may thus be used to estimate crop growth stage. R^2 was only 0.57 for index 3. This is explained as follows: temperature differences between stressed and non-stressed areas occur only when atmospheric demand for water is sufficiently great. When atmospheric demand is low, no positive values accrue. The lack of correlation (R^2 = 0.02) for index 2 is due to the fact that differences between canopy temperature and air temperature fluctuate in both sign and magnitude according to atmospheric demand. Consequently, index 2 may be positive or negative on a given day. Index 2 is not suitable for estimating crop development. Index 1 is the most convenient index for estimating growth stage, since only one daily measurement is required instead of the two daily measurements required by indices 4 and 5. But index 1 (and index 4) will not be reliable in areas where the temperature falls below some base value (10 C in corn), since positive values will accumulate even though crop development has ceased. For such conditions index 5 is more suitable.

Crop growth stage, as predicted by index 1, was compared with weekly phenological measurements from plots which were not included in development of the correlations in Fig. 1. The agreement between predicted and observed stage of growth was good (R^2 = 0.98) (Fig. 2).

These results suggest that crop temperature data obtained with infrared thermometers or from airborne or satellite scanners can be used to predict phenological growth stages. This may be particularly valuable when air temperature data near the surface

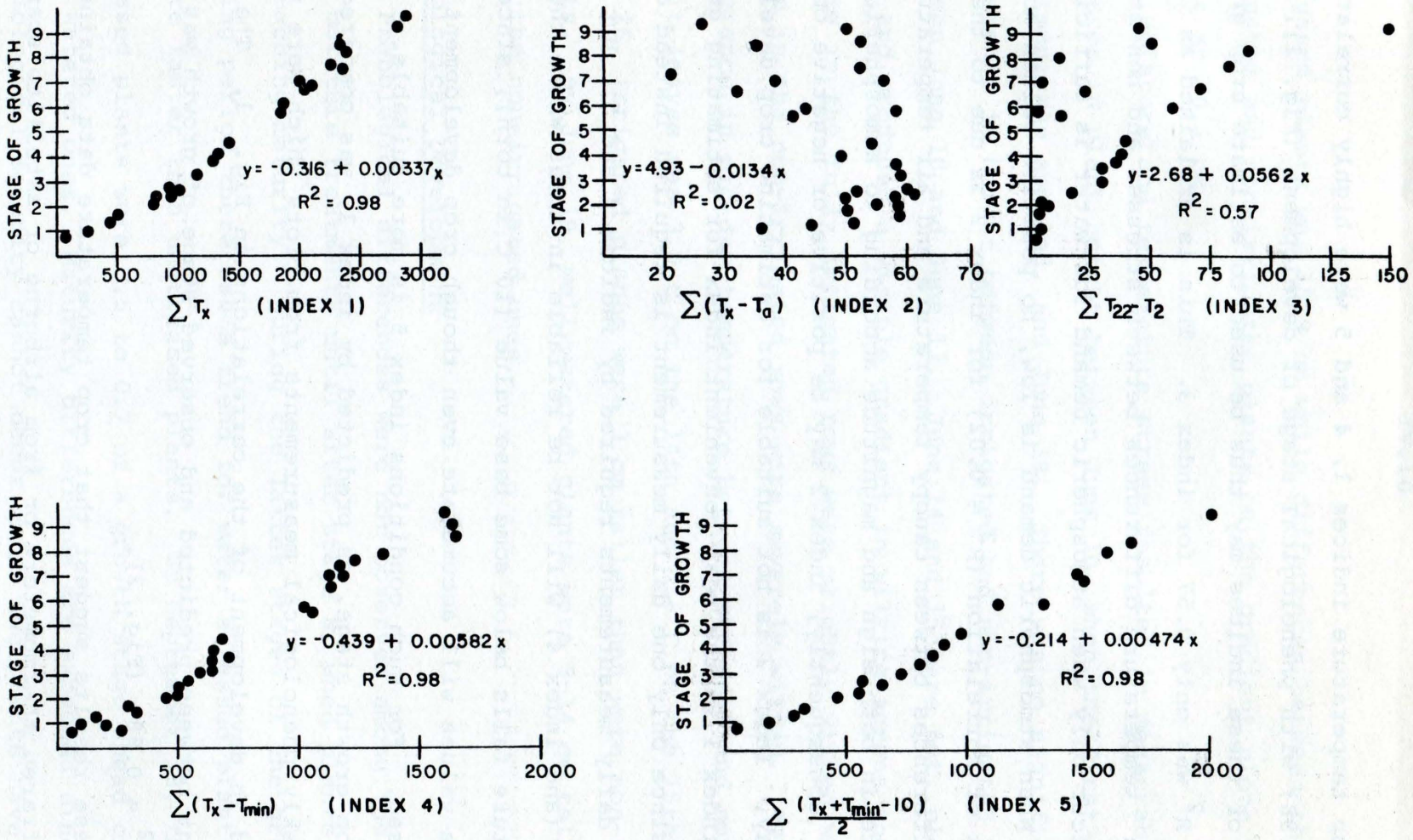


Fig. 1. Relationship between crop growth stage and the five crop temperature indices defined in Table 2.

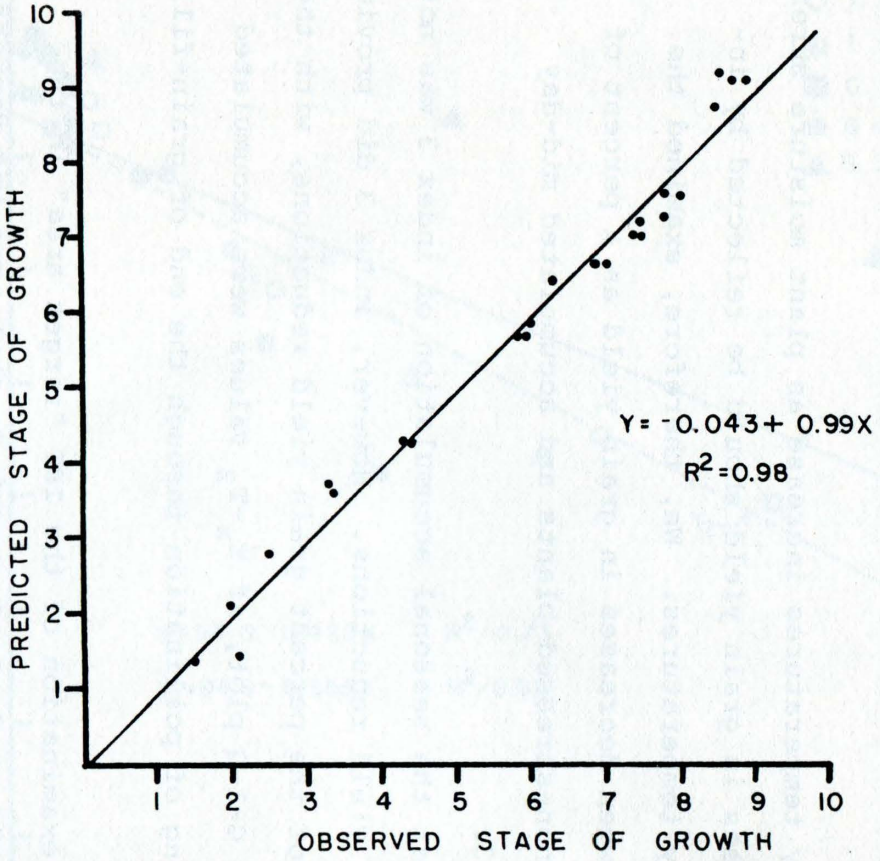


Fig. 2. Observed stage of growth versus that predicted by index 1. Predicted stage of growth = -0.316 + 0.00337x, where x equals the summation of mid-day canopy temperature (crop index 1).

is unavailable to compute growing degree days.

Grain Yields

Stress during vegetative growth only (G-I-I) had the least damaging effects on yield, while stress during both the grain-filling and pollination stages (I-G-G and G-G-G) had the greatest limiting effect on yield. Yields were moderately reduced when stress was avoided during either pollination or grain-filling (I-I-G; I-G-I; G-I-G; and G-G-I). The average grain yield on the fully irrigated rows of all plots was 123 ± 4 q/ha (196 ± 6 bu/acre).

Since canopy temperatures increase as plant moisture stress develops, decreases in grain yield should be reflected by increases in canopy temperatures. We, therefore, examined the relationship between decreases in grain yield as a percent of the yield among non-stressed plants and accumulated mid-day values of index 3.

We found that the seasonal accumulation of index 3 was not related to grain yield reductions. However, index 3 did provide a good estimate of the percent grain yield reductions, with the exception of the G-I-G plot, if T_x-T_2 values were accumulated from the beginning of pollination through the end of grain-filling (Fig. 3).

A detailed examination of the IRT "target area" in the G-I-G plot revealed that plant growth in that area was depressed, probably because of a micro-nutrient deficiency (Gardner and Blad, 1980).

The depressed area in the G-I-G plot extended into only part of the yield sampling area. Therefore, the temperature in the

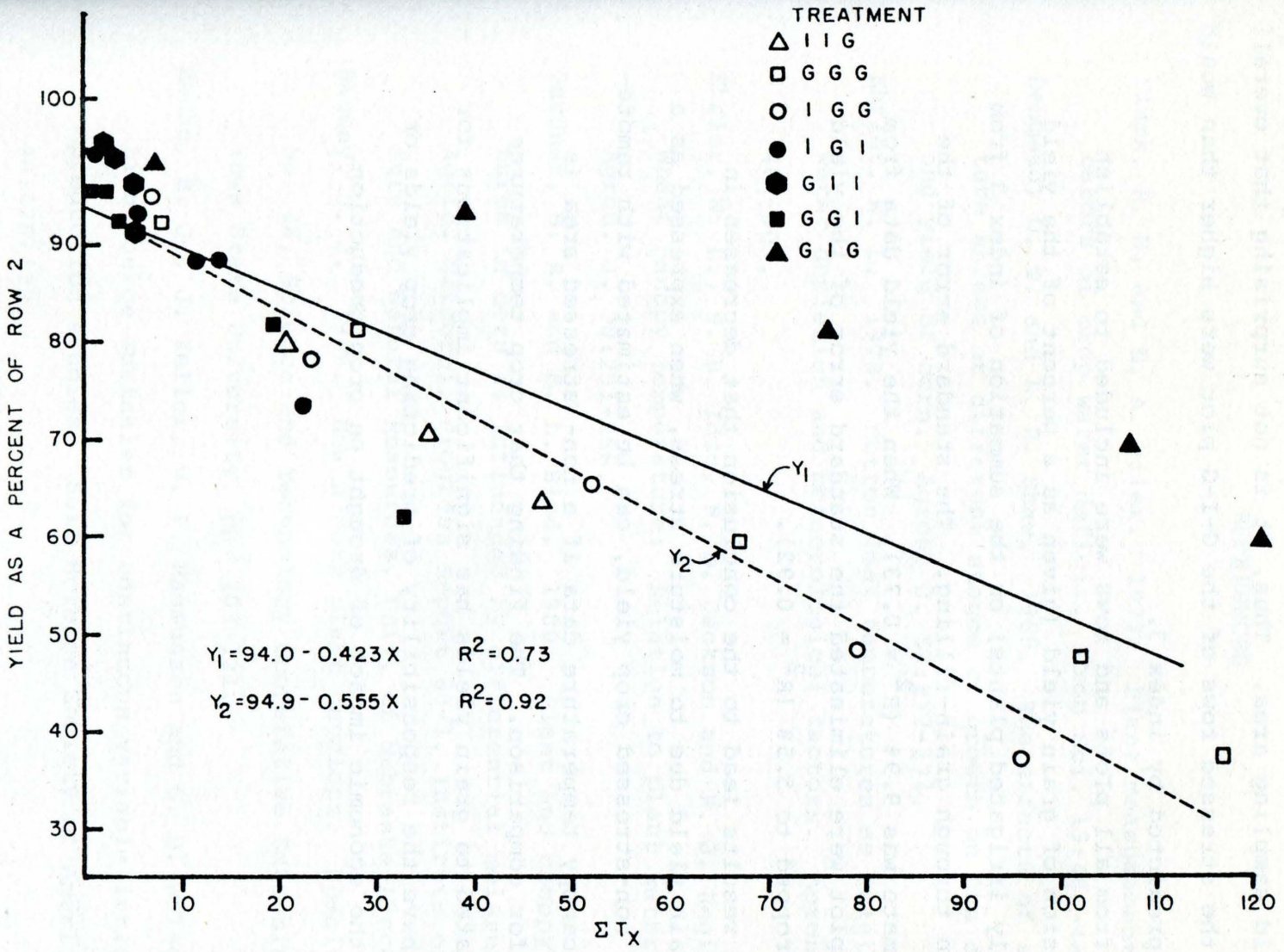


Fig. 3. Regression of grain yield (as a percent of the yield from fully irrigated plants) on the sum of index 3 from July 19 - September 13, 1978 (beginning of pollination to harvest). Y_1 includes the data from all plots. Y_2 excludes the data from the G-I-G plot.

"target area" for IRT measurements did not reflect plant performance in the yield sampling area. Thus, it is not surprising that overall yields on the stressed rows of the G-I-G plot were higher than would have been predicted by index 3.

Data from all plots and rows were included to establish the regression of grain yield (given as a percent of the yield of the fully irrigated plants) on the summation of index 3 from pollination through grain-filling. The standard error of the yield estimate was 9.9% (R^2 = 0.73). When the yield data from the G-I-G plot were eliminated the standard error of the yield estimate dropped to 5.5% (R^2 = 0.92).

These results lead to the conclusion that decreases in optimum grain yield due to moisture stress, when expressed as a percent of non-stressed crop yield, can be estimated with remotely sensed canopy temperature data if a non- stressed area is available for comparison. The finding that crop temperatures can be related to grain yields has significant implications for those who have the responsibility of predicting crop yields or assessing the economic impact of drought on crop production.

REFERENCES

Clark, R. N. and E. A. Hiler. 1973. Plant measurements as indicators of crop water deficit. Crop Sci. 13:466-469.

Denmead, O. T. and R. H. Shaw. 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52:272-274.

Ehrler, W. L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J. 65: 404-409.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978a. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.

Gardner, B. R. and B. L. Blad. 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. Agric. Meteorol. Progress Report 80-1, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln.

Hanway, J. J. 1966. How a corn plant develops. Special Report No. 48, Science and Technology Cooperative Extension Service, Iowa State University, pp. 103-121.

Hanks, R. J., J. Keller, V. P. Rasmussen and G. D. Wilson. 1976. Line source sprinkler for continuous variable irrigation-crop production studies. Soil Science Society of America Journal 40:426-429.

Hsiao, T. C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Idso, S. B., R. J. Reginato and R. D. Jackson. 1977. Remote sensing of crop yields. Science 196:19-25.

Jackson, R. D., R. J. Reginato and S. B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Res. Research 13:651-656.

Nulsen, R. A. and G. W. Thurtell. 1978. Recovery of corn leaf water potential after severe water stress. Agron. J. 70: 903-906.

Reicosky, D. C., R. B. Campbell and C. W. Doty. 1975. Diurnal fluctuation of leaf-water potential of corn as influenced by soil matric potential and microclimate. Agron. J. 67: 380-385.

Sionit, N. and P. J. Kramer. 1977. Effect of water stress different stages of growth of soybean. Agron. J. 69:274-278.

Somerhalder, B. R. 1962. Design criteria for irrigating corn. Agric. Eng. June:336-348.

Steinmetz, S. 1977. Temperatures of alfalfa, sorghum, soybean and grass as measured with leaf thermocouples and an infrared thermometer. Agric. Meterol. Progress Report 77-3, Institute of Agriculture and Natural Resources, Univ. of Nebraska-Lincoln, pp. 71-73.

CHAPTER V

PLANT AND AIR TEMPERATURES IN DIFFERENTIALLY IRRIGATED CORN

B. R. Gardner, B. L. Blad and D. G. Watts

ABSTRACT

Studies by Jackson et al. (1977) and Idso et al. (1977) indicate that wheat is not stressed for water unless leaf temperature exceeds air temperature. One objective of the study reported here was to evaluate the effects of varying levels of plant water stress and crop temperature with the aim of providing practical water resource management tools. The third objective was to determine relationships between leaf temperature and air temperature within corn canopies as a function of water stress.

Meteorological, physiological and phenological measurements were made in nine plots of corn (Zea mays L.), grown on Valentine fine sand (Typic ustipsamment) at the Sandhills Agricultural Laboratory (SAL). Each plot received one of seven different irrigation treatments. Canopy temperatures were measured with an infrared thermometer at mid-day throughout the growing season. Air and leaf temperature measurements were made on an hourly basis with thermocouples. Physiological and phenological observations were made weekly.

The average mid-day difference in canopy temperature between stressed and non-stressed areas was as large as 7.0 C. In fully irrigated plots, the standard deviation of mid-day canopy temperature was about 0.3 C but in non-irrigated areas it reached, at times, 4.2 C. We conclude that, a standard deviation of temperature in a plot, exceeding 0.3 C, signals that some plants

are experiencing water stress. This behavior can indicate the need for irrigation.

Daily profiles of leaf and air tempreature in stressed and non-stressed canopies were found to be similar. Profiles tended to be lapse before crop cover was complete and inverted later in the season. At any level within the stressed canopy, plants were warmer than at the same level within the non-stressed canopy. The mid-day temperature of sunlit leaves of non-stressed and moderately stressed plants was generally 1-2 C below air temperature. The temperature of sunlit leaves in severely stressed plants were as much as 4.6 C above air temperature. We observed that, contrary to some previously published results, corn plants may be subject to some water stress and still be cooler than the air temperature.

INTRODUCTION

The leaves of moisture stressed plants have been found to be warmer than those of non-stressed plants. Temperature differences between stressed and non-stressed leaves reported for various crops range from +2 to +8 C (Miller, 1923; Eaton, 1929; Millar et al., 1971; Ehrler et al., 1978).

Wiegand and Namken (1966) found that the difference in temperature between stressed and non-stressed cotton (Gossypium hirsutum L.) leaves ranged from 2.5 to 4.5 C when solar radiation flux density was 200 Wm^{-2} and 1100 Wm^{-2}, respectively.

Tanner (1963) suggested that the temperature difference between stressed and non-stressed potato (Solanum tuberosum) leaves gave a qualitative indication of their transpiration differences.

He concluded that, with a better understanding of heat and vapor transfer processes at the plant surface, leaf temperature measurements could provide quantitative data on plant water status.

Ehrler (1973) stated that long-term measurements of leaf temperature provide an indirect indication of stomatal behavior. Ehrler et al. (1978) demonstrated that canopy temperature in wheat increased as plant water potential decreased. Differences in canopy temperature between stressed and non-stressed wheat plants were shown to be a reliable indicator of plant moisture status.

Clark (1973) stated that stomatal resistance in peas (Vigna sinensis L.) increased as moisture stress developed, resulting in increased leaf temperature. He concluded that the status of water in plants represents an integration of the atmospheric demand, soil-water potential, rooting density and distribution and other plant characteristics. Thus, for a true measure of plant moisture deficit, measurements should be made on the plant instead of in the soil or the atmosphere.

Aston and van Bavel (1972) and Nixon et al. (1973) suggest that a large variability in canopy temperature should signal the onset of soil moisture deficits due to the inhomogeneous moisure retention properties in large fields. Ehrler (1973) and Ehrler et al. (1978) showed that the differential in leaf-air temperature can be used to signal the need for irrigation. Ritchie (1977) suggested using the temperature difference between stressed and non-stressed plants to detect the occurrence of soil moisture deficits.

In view of the above-stated findings a study was designed

with the following objectives: 1) to evaluate the effects of varying levels of plant water stress on crop temperatures; 2) to establish the relationship between plant water stress and crop temperature in corn with the aim of providing practical water resource management tools (e.g. irrigation scheduling, drought surveillance); and 3) to determine relationships between leaf temperature and air temperature within corn canopies as a function of water stress.

METHODS AND MATERIALS

The study was conducted at the University of Nebraska Sandhills Agricultural Laboratory, located near Tryon, Nebraska (41° 47' N; 100° 50' W; 975 m above m.s.l.). Details of the experimental site and research procedures are given in Chapter II.

Seven combinations of two basic irrigation treatments were applied to nine plots of corn (Zea mays L. cv. Pioneer 3780) (Table 1). The full irrigation treatment (I) consisted of resupplying by irrigation 100% of the water used to all rows in a plot. The amount of water consumed by evapotranspiration was determined by measuring soil moisture depletions with a neutron probe. The gradient treatment (G) consisted of applying full irrigation to row 1 of a plot and applying progressively less moisture to each succeeding row, until rows 22 through 24 received essentially no irrigation.

Canopy temperatures were measured with an infrared thermometer (IRT) each day between 1200 and 1330 solar time on rows 2, 6, 10, 14, 18 and 22 and of each plot. Readings began on June 1 and continued throughout the growing season, except for a few days

Table 1. The seven irrigation treatments used for the study. I means that all rows in a plot received a full irrigation during that growth period. G means that an irrigation gradient was established so that one side of the plots received 100% of its water needs, while the opposite side received essentially none of its needs.

	Growth Stage		
Treatment	Vegetative	Pollination	Grain Filling
1	G	I	I
2	I	G	I
3	I	I	G
4	G	I	G
5	I	G	G
6	G	G	G
7	G	G	I

when measurement was not possible. Two infrared thermometers were used. A Telatemp model 44 was used between June 13 and July 17. A Barnes model PRT-5 was used for the remainder of the season. The maximum width of the spot seen by the IRT's was calculated to be 95 cm and the maximum length 200 cm. The viewing angle decreased from about 22 to about 15 degrees from the horizontal as the crop increased in height.

Detailed measurements of leaf and air temperature profiles were made in one plot (hereafter, called the instrumented plot). Air and leaf temperatures were measured at 3 different levels within the canopy in rows 2, 6, 10, 14, 18 and 22. The bottom, middle and top of the canopy were designated levels 1, 2 and 3, respectively. Air thermocouples in levels 2 and 3 were raised as the crop grew. The crop reached its full height by July 26 and no further adjustments in instrument height were made after that date.

Leaf temperatures were measured at each level with a set of 5 or 6 evanohm-constantan thermocouples (0.13 mm diameter) which were wired in parallel. The junctions of each thermocouple junction were taped to the lower surface of different leaves, using the method described by Steinmetz (1977).

Copper-constantan air thermocouples, in 6 mm diameter teflon plugs to dampen rapid fluctuations in air temperature, were placed in level 3. One air thermocouple was mounted permanently at a height of 3 meters above ground in row 2.

RESULTS AND DISCUSSION

Temperature Differences Between Stressed and Non-Stressed Areas

The average mid-day IRT-measured temperature difference between row 22 and row 2 (notated as $*T_{22} = T_{22} - T_2$) was larger on gradient (G) plots than on fully irrigated (I) plots. This effect is noted during the vegetative (Fig. 1), the pollination (Fig. 2) and the grain-filling (Fig. 3) periods. Another noteworthy feature is the greater standard deviation of *T (σ_T) in G and in I plots.

σ_T, which represents the mid-day spatial variability in canopy temperature, averaged 1.0 C on I plots and 1.2 C on G plots prior to July 10 (approximately full plant cover). After July 10, σ_T decreased to 0.3 C on I plots but remained about 1.2 C on G plots (Table 2), though on some days σ_T on G plots was as great as 4.2 C. The large temperature variability in the G plots results from microscale variations in soil water retention characteristics and from differences in the amount of irrigation applied to row 22 at various growth stages. In some G plots row 22 was fully irrigated during a previous growth period but in some plots it had received no irrigation. On several days during the pollination period σ_T was small because of cool, cloudy and wet weather.

Inspection of Fig. 1 indicates that rainfall or irrigation had only a minor effect on σ_T during much of the vegetative period. However, during the late vegetative, pollination and grain-filling periods, σ_T on well-irrigated plots increased prior to irrigation and decreased after irrigation on July 13, July 26, August 17 and September 1.

Heermann and Duke (1978) found that σ_T in well-irrigated corn

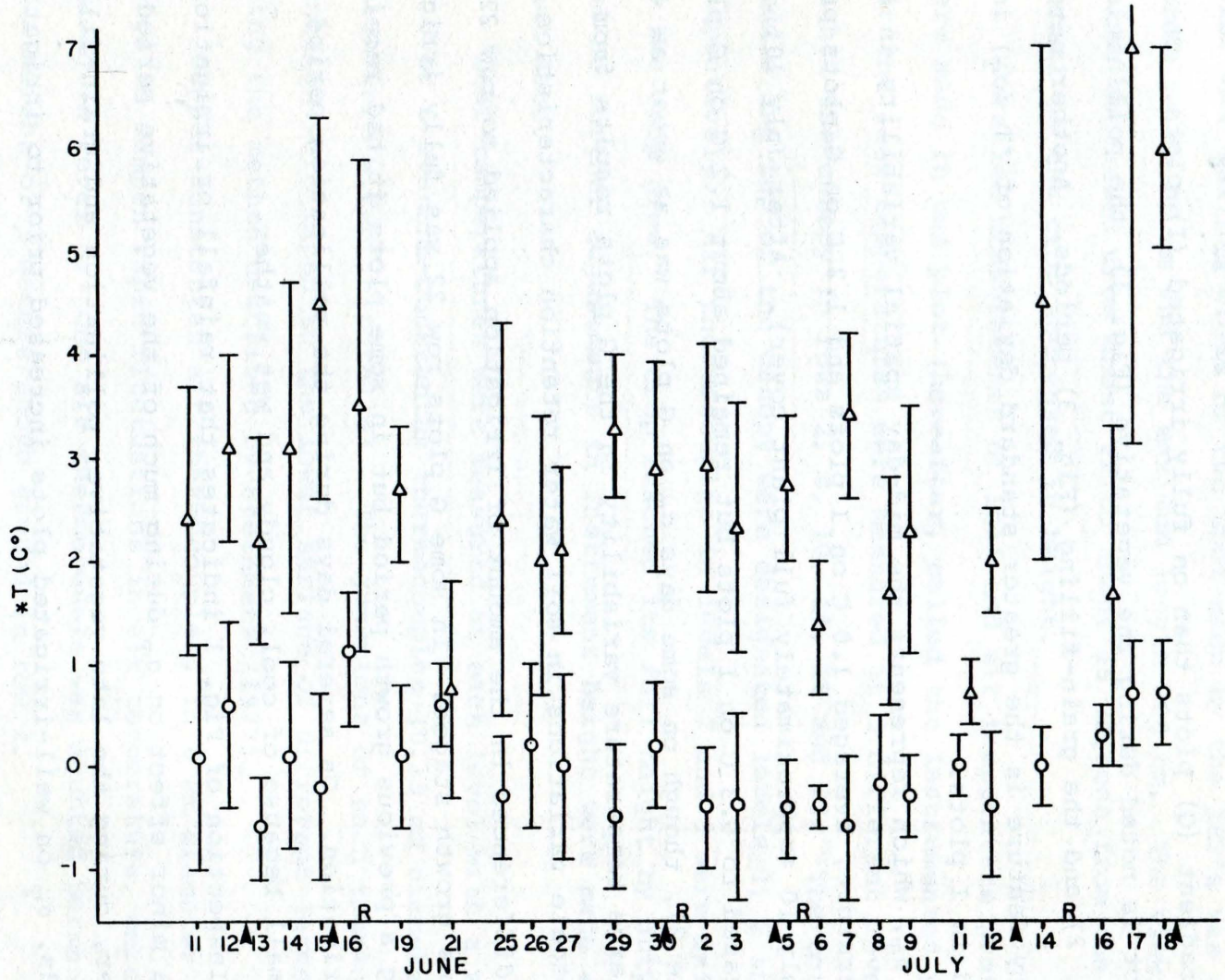


Fig. 1. The average difference in mid-day canopy temperature between row 22 and row 2 (*T) on plots receiving a gradient treatment (Δ) and in fully irrigated plots (o) during vegetative growth. Standard deviation (σ_T) of each data point is indicated with a bar. The occurrence of rainfall is indicated with an R and irrigations are indicated with arrows.

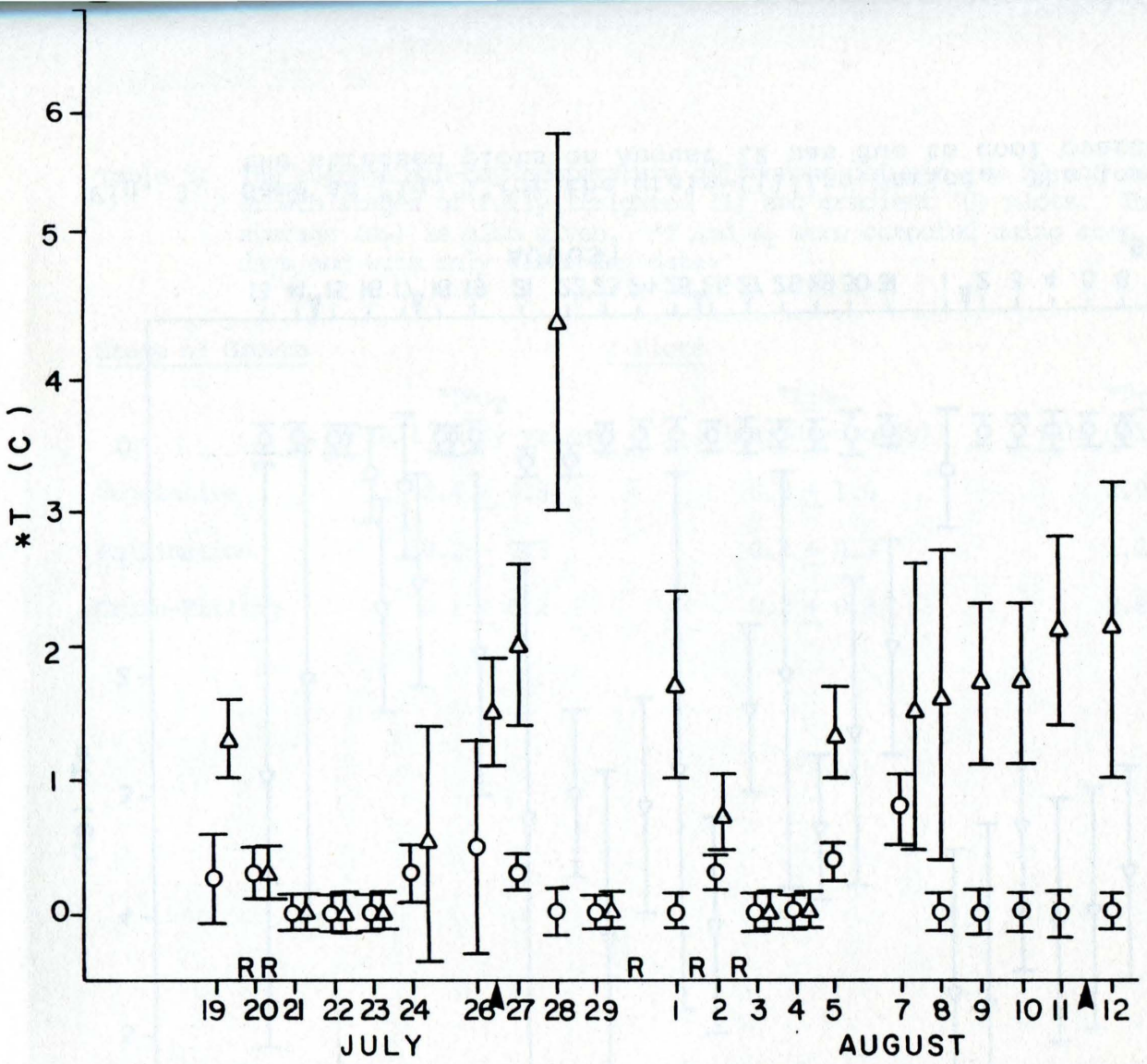


Fig. 2. Same as Fig. 1 for the pollination period.

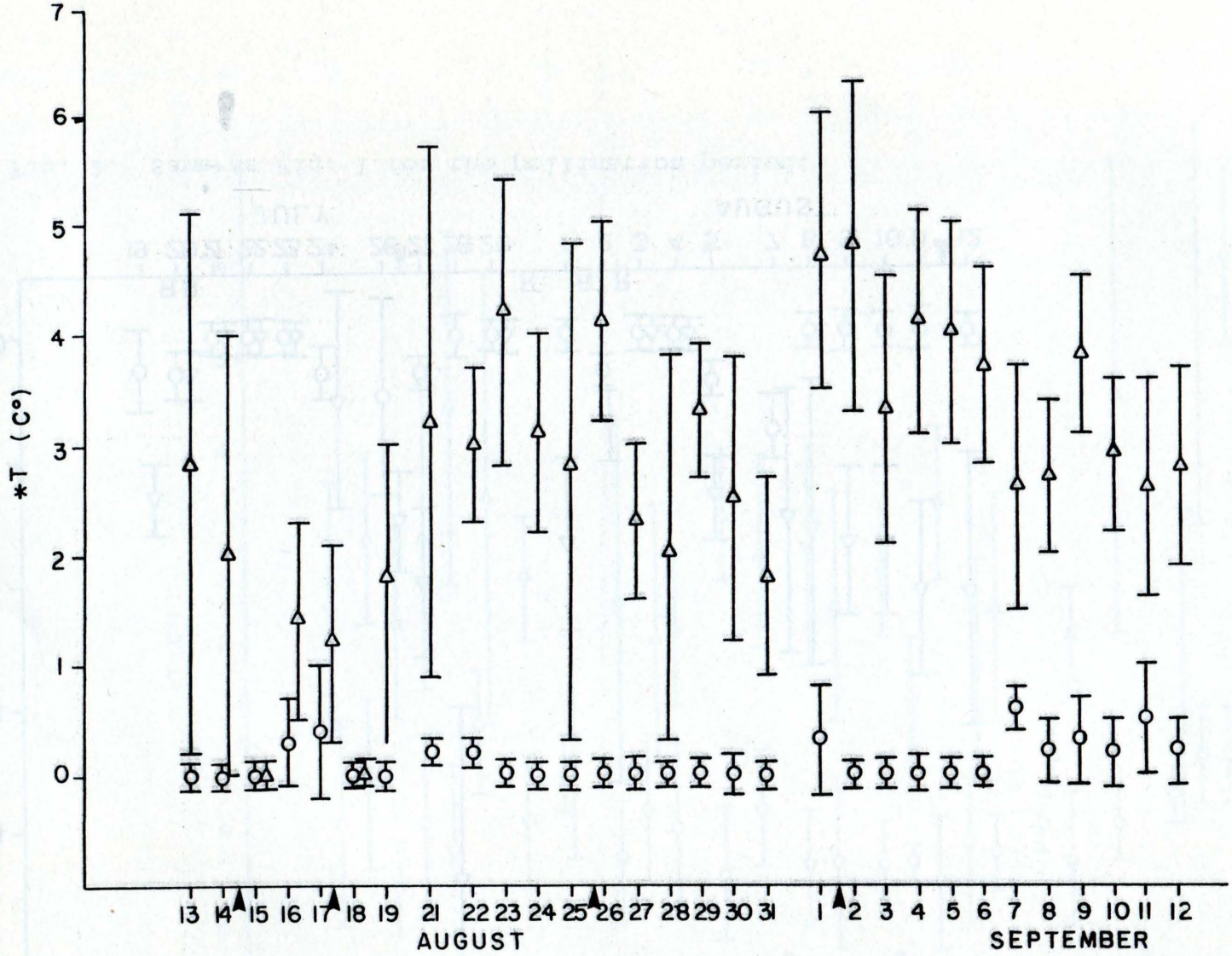


Fig. 3. Same as Fig. 1 for the grain-filling period. The low *T and σ_T value for the stressed plots on August 18 was due to cool overcast weather.

Table 2. The average mid-day temperature difference between row 22 and row 2 (*T) for the different growth stages of fully irrigated (I) and gradient (G) plots. The standard deviation of each average (σ_T) is also given. *T and σ_T were computed using crop temperatures obtained on all days and with only clear day data.

Stage of Growth	I Plots		G Plots	
	$*T \pm \sigma_T$ (All daily values)	$*T \pm \sigma_T$ (clear days only)	$*T \pm \sigma_T$ (All daily values)	$*T \pm \sigma_T$ (clear days only)
Vegetative	0.4 ± 0.8	0.2 ± 1.0	2.9 ± 1.3	2.7 ± 1.12
Pollination	0.2 ± 0.3	0.2 ± 0.3	1.2 ± 1.1	1.8 ± 1.0
Grain-Filling	0.1 ± 0.2	0.2 ± 0.3	2.8 ± 1.2	3.1 ± 1.1

at oblique viewing angles was around 0.2 C but at vertical viewing angles σ_T was approximately 1.5 C. σ_T may change as a function of soil type and crop, as well as IRT viewing angle. At the oblique IRT viewing angles used in this study values of σ_T above 0.3 C resulted when some plants began to experience water stress.

On the basis of these findings, it appears that the irrigations on July 13, July 26 and August 17 were a day or so too late to prevent stress in the well-watered plots, while the irrigation of September 1 was timely - applied as it was on the evening of the day on which stress was first observed. The irrigations of August 11, 14 and 25 were made prior to the appearance of plant stress. All irrigations had been scheduled with the aid of the neutron probe. That method, apparently, gave satisfactory results.

These findings suggest the possibility of using *T and σ_T measurements to evaluate and compare the effectiveness of various methods for scheduling irrigation and for evaluating the uniformity of water application with different irrigation systems and techniques. If these measurements can be made from aircraft or satellite platforms they may also offer the potential for evaluating the severity of drought on a regional basis. The use of σ_T to schedule irrigations also offers possibilities. When σ_T increased above the average expected value - 0.3 C in this study - the need for irrigation was indicated.

Plant Temperature as an Indicator of Severity of Stress

Differences in temperature between stressed and non-stressed areas did not begin to develop, typically, until after 1100 solar time. However, on September 1, in the instrumented plot, $*T_{22}$ was

1.5 C at 0800 and 3.5 C at 0900 hrs, indicating tht stomata were already closing on the plants in row 22. This probably reflects an increase in the severity of water stress experienced by the plants and suggests that *T measurements may be used, as well, to distinguish the degree of plant water stress. This hypothesis is explored in further detail in Chapter VIII.

Daily Patterns of Leaf and Air Temperature

Before crop cover was complete in the instrumented plot, the leaf temperature profiles tended to be isothermal in both stressed and non-stressed areas during the day. Temperature differences across the plot occurred at each level within the canopy. After crop cover was complete the leaf temperature profiles during the day were generally inverted. This was due, primarily, to the absorption of solar radiation by leaves near the top of the canopy and the shading of leaves within the canopy. Differences in leaf temperatures at each level with the canopy across the plot persisted because of reduced transpiration in the water stressed plants.

A typical daily pattern of thermocouple measured leaf and infrared measured canopy temperatures under conditions of clear skies with moderately strong winds is given in Fig. 4. Canopy temperatures measured with the IRT closely followed the temperature of sunlit leaves (level 3) in both the stressed and non-stressed areas (row 22 and row 2, respectively).

The vertical air temperature gradients (Fig. 5), in the non-stressed row (2) followed the same pattern as the leaf temperature gradients, that is both were inverted. However, in the more open

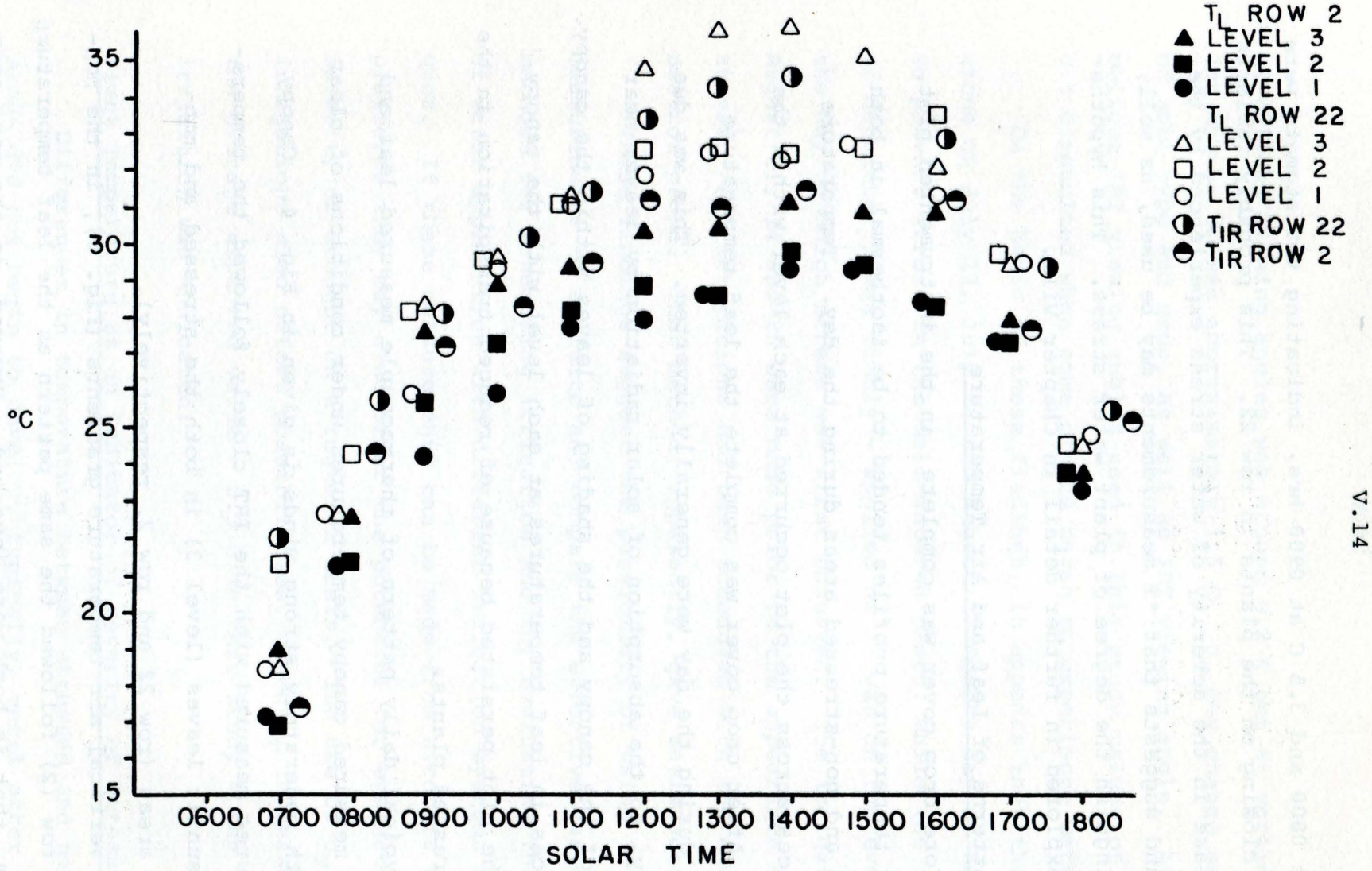
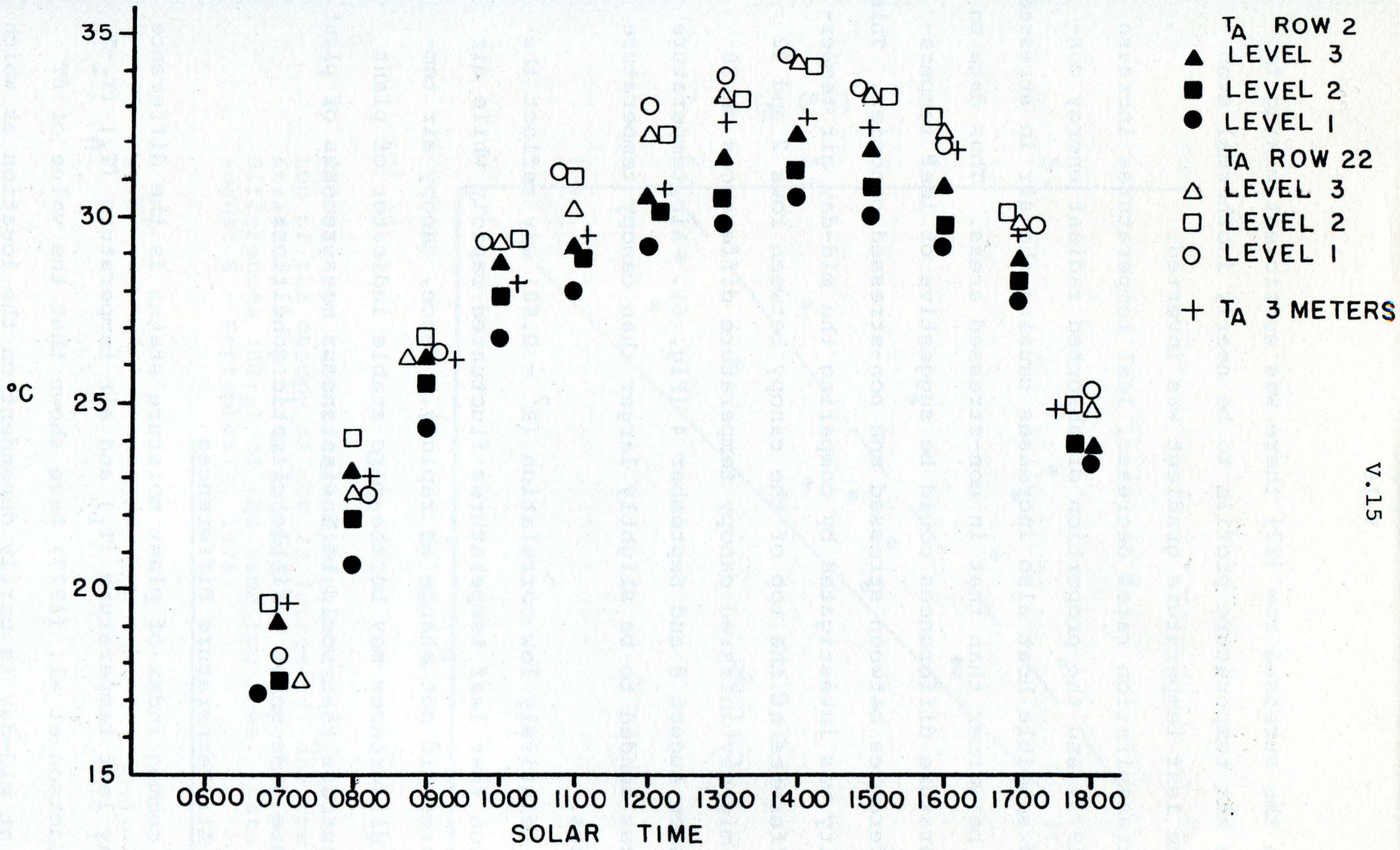


Fig. 4. Daily pattern of leaf temperatures on August 22, 1978, in row 2 (non-stressed) and row 22 (stressed) at the bottom of the canopy (level 1), middle of the canopy (level 2) and at the top of the canopy (level 3). Infrared canopy temperatures (T_{IR}) are also plotted.



V.15

Fig. 5. Daily pattern of air temperature (T_A) on August 22, 1978, in row 2 and row 22 at the bottom of the canopy (level 1), the middle of the canopy (level 2) and at the top of the canopy (level 3). Air temperature at three meters above the soil surface in row 2 is included.

canopy in the stressed row (22) there was sufficient mixing to cause the air temperature profile to be nearly isothermal even though the leaf temperature gradient was inverted.

As transpiration rates decrease, leaf temperatures increase (Hsaio, 1973) and the proportion of absorbed radiant energy converted to sensible heat also increases causing the air in stressed areas to be warmer than that in non-stressed areas. Thus data on air temperature differences could be suggestive of leaf temperature differences between stressed and non-stressed canopies. This possibility was investigated by comparing the mid-day air temperature difference at the top of the canopy between rows 2 and 22 with the mid-day infrared canopy temperature differences on 20 days between August 8 and September 4 (Fig. 6). Air temperature differences tended to be slightly larger than canopy temperature differences.

The relatively low correlation ($R^2 = 0.60$) may reflect the observation that leaf temperatures fluctuated rapidly while air temperatures did not change as rapidly. Hence, canopy air temperature differences may be the more stable indicator of plant moisture stress than would be instantaneous measurements of plant temperature made under variable climatic conditions.

Leaf and Air Temperature Differences

One common index of plant moisture status is the difference in mid-day leaf temperature (T_L) and air temperature (T_A) ($T_L - T_A = \Delta T$). Jackson et al. (1977) have shown that the value of ΔT obtained at mid-day is partly dependent on the location at which air temperature (T_A) is measured. Accordingly, we computed ΔT

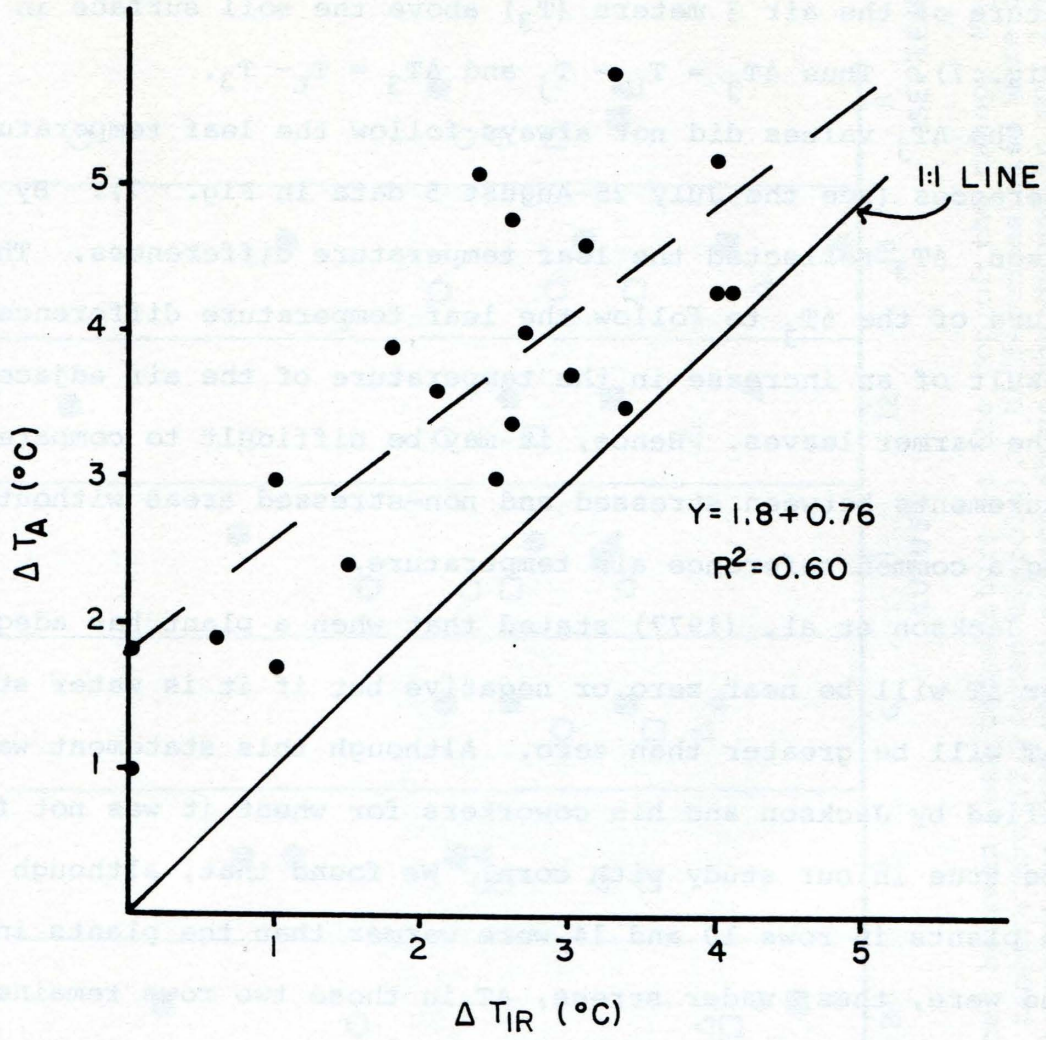


Fig. 6. Mid-day air temperature differences (ΔT_A) between the top of the canopy of row 22 (stressed) and row 2 (non-stressed) in plot 22 and mid-day canopy temperature differences (ΔT_{IR}) of the same two rows. Data are from August 8 - September 4, 1978.

of leaves at the top of the canopy in rows 2, 10, 14 and 22 using the temperature of the adjacent air (T_j) in each row or the temperature of the air 3 meters (T_3) above the soil surface in row 2 (Fig. 7). Thus $\Delta T_j = T_L - T_j$ and $\Delta T_3 = T_L - T_3$.

The ΔT_j values did not always follow the leaf temperature differences (see the July 25-August 5 data in Fig. 7). By comparison, ΔT_3 reflected the leaf temperature differences. The failure of the ΔT_j to follow the leaf temperature differences is a result of an increase in the temperature of the air adjacent to the warmer leaves. Hence, it may be difficult to compare ΔT measurements between stressed and non-stressed areas without using a common reference air temperature.

Jackson et al. (1977) stated that when a plant has adequate water ΔT will be near zero or negative but if it is water stressed ΔT will be greater than zero. Although this statement was verified by Jackson and his coworkers for wheat it was not found to be true in our study with corn. We found that, although the corn plants in rows 10 and 14 were warmer than the plants in row 2 and were, thus, under stress, ΔT in those two rows remained negative. Only in row 22 was ΔT found to be positive. In Chapter II it was shown that yields were reduced in proportion to the degree of stress experienced by the plants in rows 10 and 14. These results suggest that corn is probably more sensitive to water stress than is wheat and that the use of ΔT values to indicate water stress are probably soil, crop and climate specific.

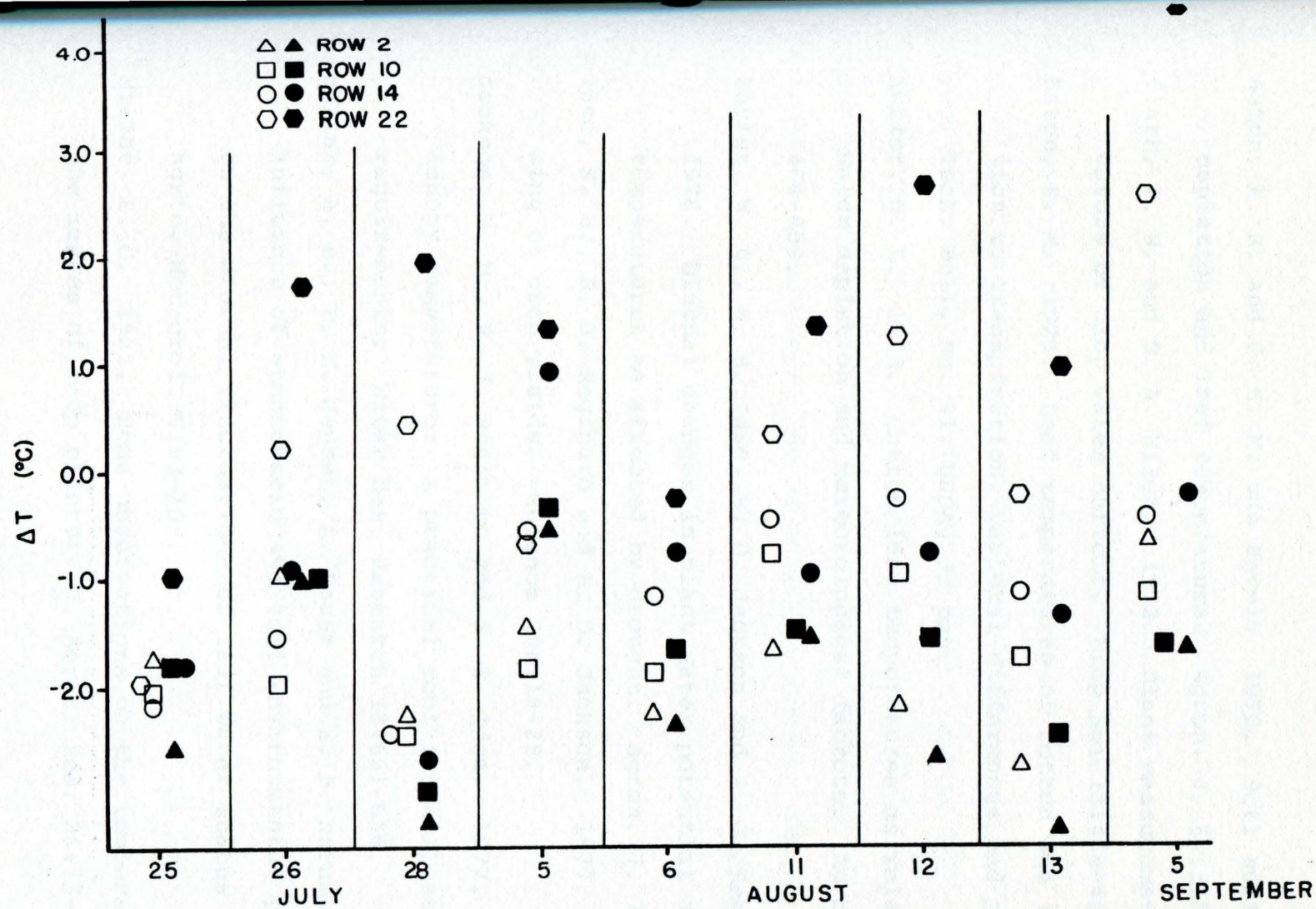


Fig. 7. Mid-day differences between leaf temperature at the top of the canopy (T_L) and adjacent air temperature (T_j) (open symbols). Differences also were computed using air temperature from three meters above the ground in row 2 (T_3) (closed symbols). Calculations were performed on data from rows 2, 10, 14 and 22 on plot 22 for nine clear days between July 25 and September 5, 1978.

REFERENCES

Aston, A. R. and C. H. M. van Bavel. 1972. Soil surface water depletion and leaf temperature. Agron. J. 64:368-373.

Clark, R. N. and E. A. Hiler. 1973. Plant measurements as indicators of crop water deficit. Crop Sci 13:466-469.

Eaton, F. M. 1929. Leaf temperatures of cotton and their relation to transpiration, varietal differences and yields. Tech. Bull. No. 91, USDA, 39 pps.

Ehrler, W. L. 1973. Cotton leaf temperatures as related to soil water depletion and meteorological factors. Agron. J. 65: 404-409.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978. Diurnal changes in plant water potential and canopy temperatures as affected by drought. Agron. J. 70:998-1004.

Idso, S. B., R. J. Reginato and R. D. Jackson. 1977. Remote sensing of crop yields. Science 196:19-25.

Jackson, R. D., R. J. Reginato and S. B. Idso. 1977. Wheat canopy temperature: A practical tool for evaluating water requirements. Water Res. Research 13:651-656.

Millar, A. A., R. E. Jensen, A. Bauer and E. B. Norum. 1971. Influence of atmospheric and soil environmental parameters on the diurnal fluctuations of leaf water status of barley. Agric. Meteorol. 8:93-105.

Miller, E. C. 1923. Some observations on the temperature of the leaves of crop plants. J. Agric. Res. 26:15-43.

Nixon, P. R., L. N. Namken and C. L. Wiegand. 1972. Spatial and temporal variations of crop canopy temperatures and implications for irrigation scheduling. Proc. Conf. on Earth Resources Observation and Information Analysis System: Remote Sensing of Earth Resources. Vol. II, F. Shahrokhi (ed.) Tullahoma, Tennessee, pp. 643-657.

Ritchie, J. T. 1977. The contribution of the surface energy balance in climatic stres for agriculture. Presented at Climate-Technology Seminar, Oct. 25-26, Columbia, Missouri, 23 pps.

Tanner, C. B. 1963. Plant temperatures. Agron. J. 55:210-211.

Wiegand, C. L. and L. N. Namken. 1966. Influences of plant moisture stress, solar radiation and air temperatures on cotton leaf temperature. Agron. J. 58:582-586.

CHAPTER VI

RELATIONSHIPS BETWEEN CROP TEMPERATURE, GRAIN YIELD, EVAPOTRANSPIRATION AND PHENOLOGICAL DEVELOPMENT IN TWO HYBRIDS OF MOISTURE STRESSED SORGHUM

B. R. Gardner, B. L. Blad, D. G. Watts and D. P. Garrity

ABSTRACT

Recent studies have shown that the grain yields of corn (Zea mays L.) and wheat (Triticum aestivum L.) are related to the degree of water stress experienced. The purpose of the study reported here was to establish predictive relationships between crop temperature and the grain yields, phenological development, evapotranspiration rates and leaf water potential values in two hybrids of grain sorghum (Sorghum bicolor L. Moench) that were subjected to varying levels of plant water stress.

The study was conducted at the University of Nebraska Sandhills Agricultural Laboratory in 1978. The sorghum hybrids used in this study were RS 626 and NB 505. Four irrigation treatments were applied in order to develop varying levels of water stress during each of three major growth stages. Soil moisture was monitored with a neutron probe. Crop temperature was measured with an IR thermometer and leaf water potential was measured with a Scholander pressure bomb.

Maximum grain yields were achieved with an irrigation treatment in which 80% of the water lost by evapotranspiration was replaced. Grain yields were reduced if water stress occurred during any growth period. Yield reductions were most severe

when stress occurred only during the grainfill period and least severe when stress occurred during the entire growing season.

The percentage reduction in sorghum grain yield was found to be well described by an index involving the seasonal accumulation of the daily temperature differences between well-watered and stressed crops (ΣTSD). The response curves had similiar slopes but different intercepts because of differences in the yield potential of the hybrids.

As ΣTSD values increased, ET decreased. However, the correlation of ET vs ΣTSD was relatively low ($R^2 = 0.60$), probably because of the relatively small amount of data available for analysis and inaccuracies in estimating ET using the soil water balance method.

We observed a temperature range of about 0.5 C between the well-watered rows in various plots for several days following an irrigation. However, in certain instances, the temperature range increased to 1-2 C for a few days before irrigation. This suggests that certain of the plots experienced water stress and should have been irrigated earlier. Yield data support that conclusion. Crop temperature appears to be a sensitive indicator of crop water stress in sorghum. If the temperature range in a uniformly treated sorghum plot exceeds about 0.5 C, the need for irrigation is indicated.

No significant difference occurred in the phenological development of sorghum as a function of water stress except in one NB 505 plot in which plants were stressed throughout the entire season. In that plot, the stressed plants lagged in development behind non-stressed plant by approximately ten days.

We examined the differences in mid-day leaf water potentials ($\Delta\psi_\ell$) and crop temperatures (ΔT) between stressed and non-stressed vegetation. As ΔT increased up to about 4 C, $\Delta\psi_\ell$ also increased. Beyond that point, $\Delta\psi_\ell$ decreased with further increase in ΔT. We attibute this behavior to stomatal closure which permitted an increase in ψ_ℓ of the stressed plants (hence reducing $\Delta\psi_\ell$) even as ΔT continued to increase.

INTRODUCTION

One particularly useful application of crop temperature data is in the detection of crop moisture stress. Temperature differences between stressed and non-stressed plants have been shown to be related to moisture stress (Palmer, 1965; Wiegand and Namken, 1966; Millar et al., 1971; Bartholic et al., 1972; Sumayao et al., 1977). Gardner and Blad (1980) and Idso et al. (1977) have provided quantitative data relating remotely sensed crop temperature to grain yields in moisture stressed corn (Zea mays L.) and wheat (Triticum pestivum L.), respectively.

It now appears that the prediction of crop yields and the assessment of economic impacts of drought can be improved by use of remotely-sensed crop temperature data. There remains a need for determination of crop temperature-plant water stress relationships for several agronomic crops. Additionally, the need exists for evaluations of varietal differences before remotely sensed crop temperature data can be used reliably.

The purpose of the study reported here was to determine the relationship between crop temperatures measured with an IR thermometer and the grain yields, phenological development,

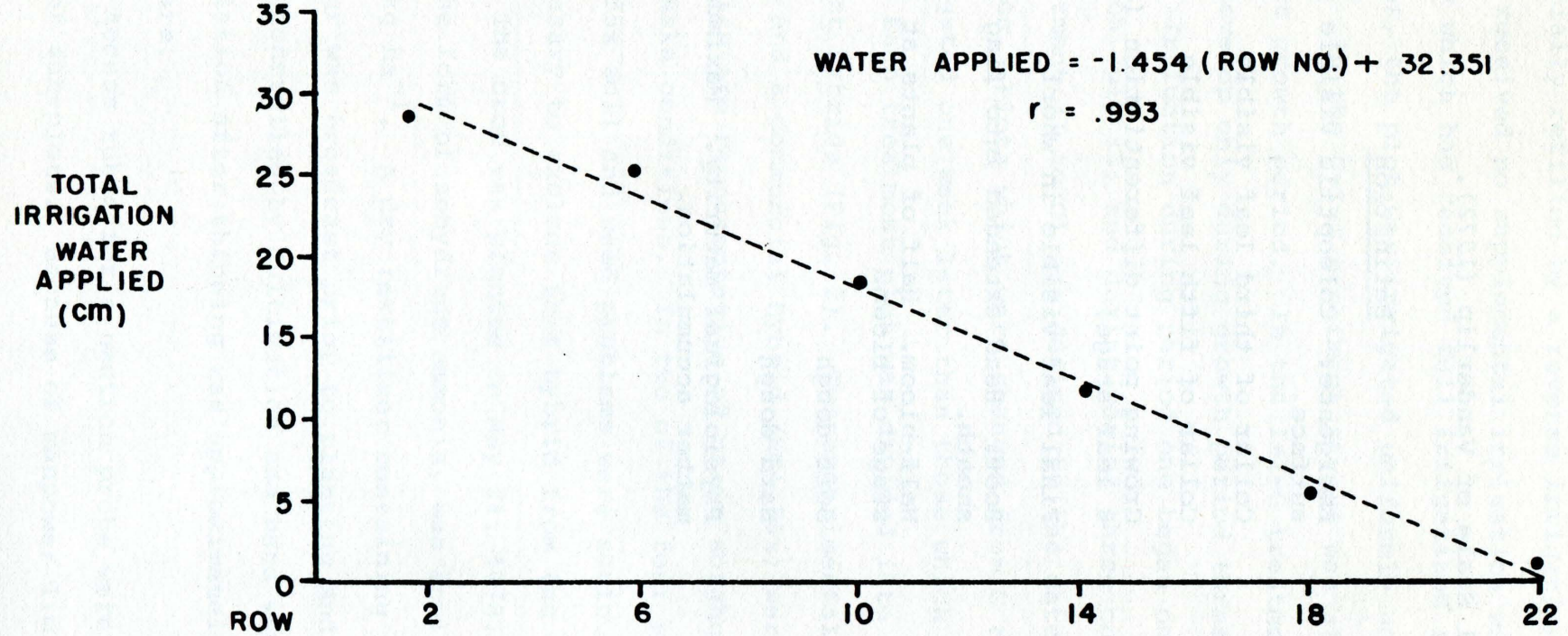
evapotranspiration rate and leaf water potential in two hybrids of grain sorghum subjected to varying levels of soil water availability and, hence, of plant water stress.

MATERIALS AND METHODS

This study was conducted in 1978 in a 12-plot area located south of and immediately adjacent to the corn experiment described in Chapter II. The same irrigation system was used in both experiments. Sorghum was planted in 76 cm rows in 24 row plots. The rows were numbered from the line irrigation source. During a gradient treatment (G), row 1 was fully irrigated with decreasing application with distance from the line until, at row 22, no irrigation water was applied (Fig. 1). In a plot receiving any I treatment, all rows were fully irrigated.

The growing season was divided into three periods. The first period began when five leaves had fully emerged. It ended prior to the appearance of the panicle in the boot, i.e., at the time when spikelet differentiation was beginning. This corresponds to Vanderlip's (1972) Growth Stage 4. The second growth period included all other reproductive events, from the boot stage through the end of bloom. Growth period three extended from the end of bloom to physiological maturity. The phenological scale used in the study is summarized in Table 1.

Four irrigation treatments were imposed in this study: G-G-G, G-G-I, G-I-I and I-I-G. In the G-G-G treatment, a moisture stress gradient was maintained in the plot during the three growth periods. In the G-G-I treatment, a moisture gradient was maintained until the end of flowering. The soil profile was then



% OF IRRIGATION ACTUALLY APPLIED	100.0	87.7	63.4	40.7	18.6	3.2
% OF IRRIGATION INTENDED TO BE APPLIED	100.0	80.0	60.0	40.0	20.0	0.0

Fig. 1. Relationship between water applied and distance from the sprinkler line, and its correspondence to the percentage of ET replaced (adapted from Gilley et al., 1980).

Table 1. Phenological Scale of Vanderlip (1972).

Growth Stage	Definition
0	Emergence. Coleoptile visible at the surface.
1	Collar of third leaf visible
2	Collar of fifth leaf visible
3	Growing point differentiation (approx. 8 leaf stage)
4	Final leaf visible in whorl
5	Boot. Head extended into flag leaf sheath.
6	Half-bloom. Half of plants at some stage of bloom.
7	Soft dough
8	Hard dough
9	Physiological maturity. Maximum dry matter accumulation.

partially refilled by a reverse irrigation, i.e., those rows which had received no supplemental irrigation were irrigated and those rows which had received full irrigatiaon received no water. Thereafter, the plot was irrigated uniformly until physiological maturity. In the G-I-I treatment stress was allowed only during the first growth period. In the I-I-G treatment stress was allowed to develop only during growth period three.

Irrigation during period one began on June 15; during period two on July 15; and during period three on August 8. Changes in treatment (I to G) are defined by the date of the last full irrigation. Plots which were changed from G to I were, in each case, irrigated one week later than those which were changed from I to G.

Each treatment plot was divided into subplots planted to different hybrids (Fig. 2). Two experimental hybrids (RS 626 and NB 505) and a commercial hybrid (NC+ 55x) were planted. The three hybrids are representative of grain sorghums adapted to central Nebraska conditions. In two of the four sub-plots planted to NC+ 55x soil and weed problems were serious. It was, therefore, necessary to exclude that hybrid from the analysis.

The crop was planted on May 24, 1978. Pre-plant nitrogen in the form of anhydrous ammonia, was applied at the rate of 220 kg ha^{-1}. A dry fertilizer containing phosphate, zinc and sulfur was broadcast prior to planting and disked in. Weeds were controlled by cultivation and hand weeding. The average population after thinning was approximately 132,000 plants per hectare.

Access tubes for a neutron probe were installed in each set of sub-plots. Because of manpower limitations soil moisture

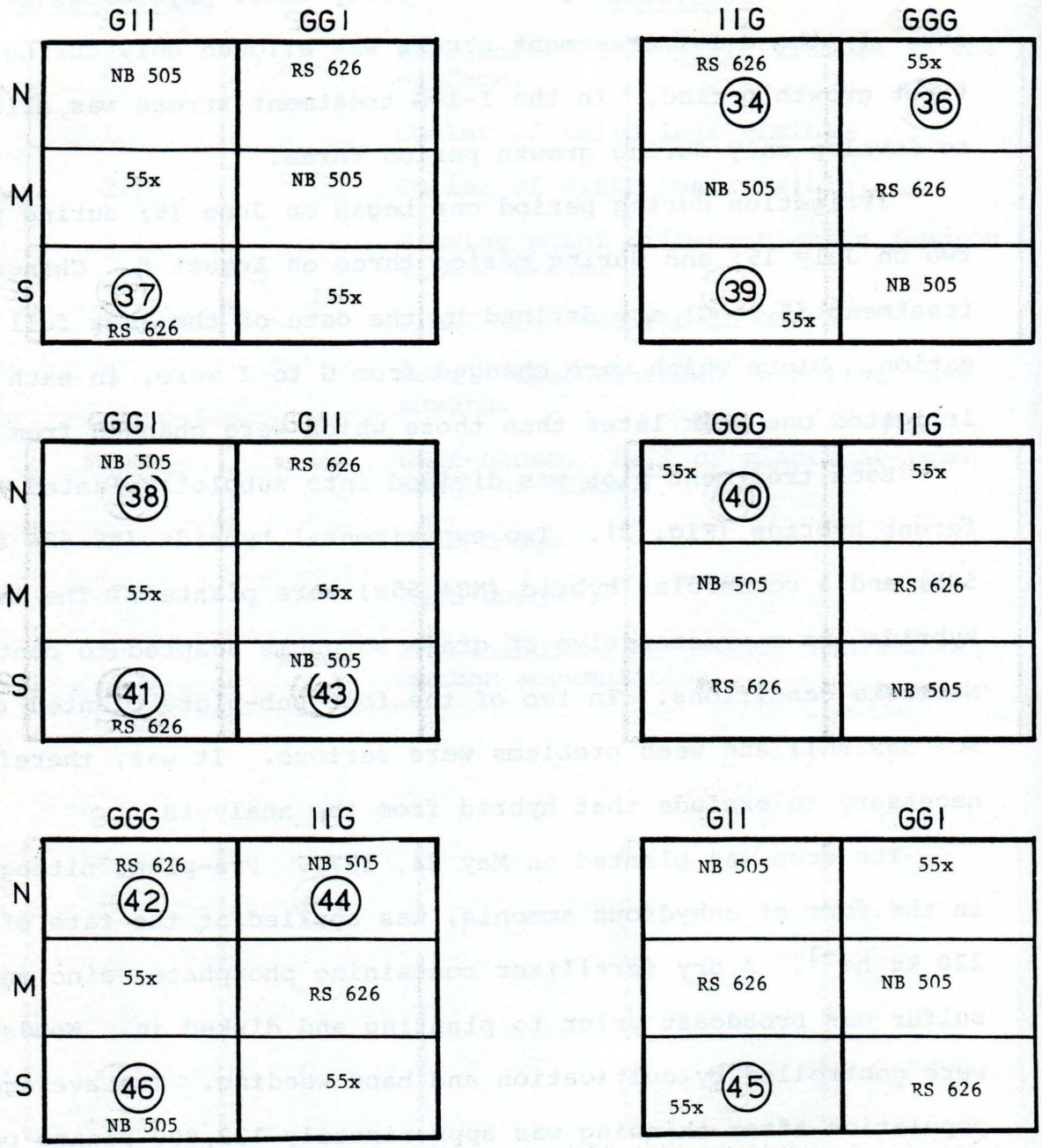


Fig. 2. Arrangement of sorghum plots used in 1978 study. Circled numbers indicate plots in which crop temperature was measured. Letters and numbers within each plot are the three sorghum hybrids. Letters above each plot indicate irrigation treatment.

was monitored in rows 14 through 22 in all plots but in rows 2 through 10 only in the middle sub-plot. Irrigations were scheduled weekly to restore water that had been depleted by evapotranspiration (ET) from the soil water profile in row 2.

Phenological observations were made at least weekly. Mid-day plant water potential measurements were made on selected clear days throughout the season in plot 42 with a Scholander pressure bomb.

Measurements were made daily throughout the growing season from atop a 12 foot ladder with a Barnes PRT 5 infrared thermometer on the selected subplots shown in Fig. 1. None of the IRT measurements were made in the middle subplots since distance from the ladder resulted in too large a spot size (2 x 6 m). In plots adjacent to the ladder, maximum width (E to W) of the observed spot was calculated to be 95 cm (approximately one row wide) and maximum length was 200 cm (N to S). In the subplots adjacent to the ladder spot-size was smaller than the yield sampling area. In the middle subplot, however, the spot-size was too great to be representative.

One crop temperature index (Index 1, Chapter IV) was tested in the estimation of crop growth stage. A temperature stress day index (TSD), defined as the mid-day crop temperature difference between the well-watered plants in row 2 and the plants in rows 6, 10, 14, 18 and 22 (Index 3, Chapter IV) was also used to estimate the reductions in yield and in ET caused by moisture stress. All IRT measurements were made using the procedures described in Chapter II.

RESULTS AND DISCUSSION

Effect of Irrigation Treatments on Evapotranspiration and Grain Yield

As expected, cumulative ET decreased as the ET replacement level decreased. The cumulative ET pattern on a G-G-G treatment for hybrid RS 626 is shown in Fig. 3. By the end of the first growth period, ET on the non-irrigated (zero % ET replacement) side of the gradient had fallen considerably below that for the non-stressed (100%) side. The gap between them continued to widen as the season progressed. Cumulative ET values for the other rows were found between these two extremes.

Maximum yields of the RS 626 hybrid for the G-G-G and G-G-I treatments occured in row 6, which received about 80% as much of the irrigation in row 2 (Fig. 4). In those cases grain yields at 80% ET replacement levels were about 800 kg ha^{-1} higher than with 100% ET replacement. For NB 505, any yield difference between 100% and 80% ET replacement levels was slight.

The less than maximal yield in the 100% ET replacement level treatment may have been due to an unfavorably humid microclimate favoring disease or insect incidence or by movement of fertilizer nutrients slightly deeper into a lower portion of the soil profile, making them less readily available to the plants. Because of the fine sand soil type, poor drainage due to overwatering is unlikely. Apparently, the adverse effects (whatever the cause) in the full irrigation environment become more pronounced as higher yield potentials are approached. Thus RS 626 was affected more adversely than was NB-505.

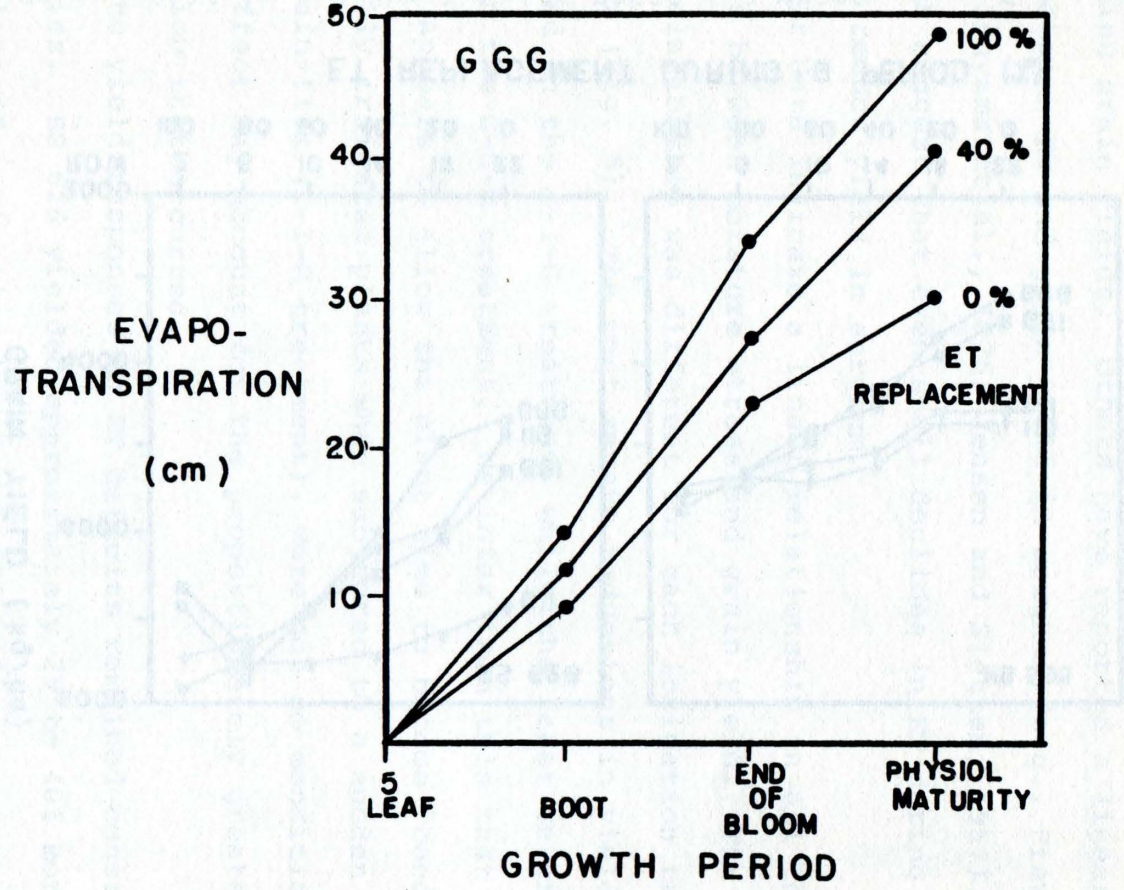


Fig. 3. The progress of grain sorghum evapotranspiration through the 1978 growing season compared among three ET replacement levels on the GGG treatment, hybrid RS626.

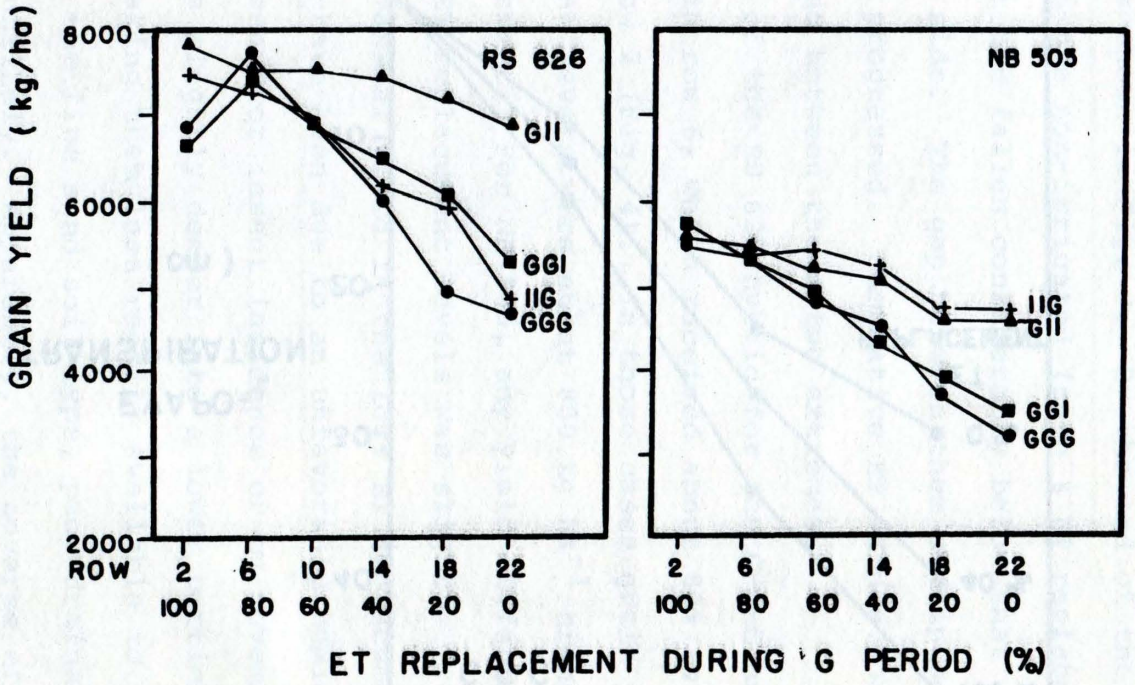


Fig. 4. Grain yield in sorghum hybrids RS626 and NB505, as a function of the percentage of ET replaced by irrigation for various irrigation treatments. Data are from the 1978 growing season at the Sandhills Agricultural Laboratory.

Early Season Stress Adaptation

The G-I-I treatment addressed the question of whether irrigation might be cut back during the vegetative and early reproductive growth stages without significant loss of grain yield. Castleberry (1973) showed that the leaf area and dry matter content of sorghum may be reduced to a considerable degree without affecting grain yields. Others have reported a linear relationship between ET and grain yield in sorghum (e.g., Stewart et al., 1974; Inuyama et al., 1976; Jensen and Sletten, 1957). These studies suggest that even small declines in ET during vegetative growth reduce yield in sorghum.

Our data indicate a linear relationship in all three growth periods between moisture stress and grain yield. The nature of this relationship was different for each irrigation treatment, however (Fig. 5). The most severe reductions in yield were observed in the I-I-G treatment, while the least severe reductions were in the G-G-G treatment. We infer from this that continuous stress appears to allow the plant time to become "conditioned." But fully irrigated plants when subjected to a sudden stress during grain-fill (I-I-G treatment), were not so conditioned and this effect may account for the proportionately greater yield reduction that occurred.

The yield responses to ET deficits remained constant between varieties. RS 626 yielded approximately 25 to 40% more than NB 505, regardless of irrigation treatment (Fig. 6). Nebraska dryland yield trial data for 1974-1978 support the conclusion that RS 626 consistently outyields NB 505 by an average of 25-30% over a wide range of environments. This may be due, in part, to the fact that

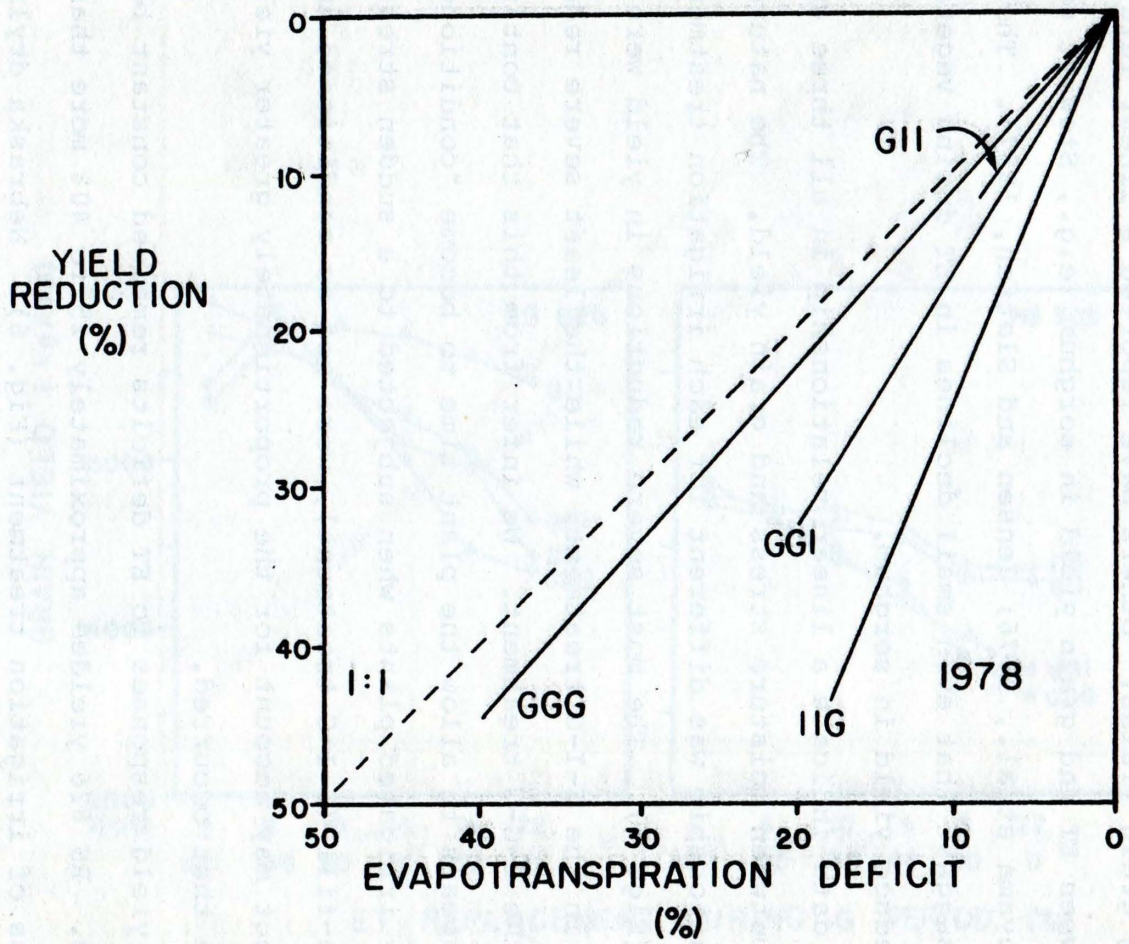


Fig. 5. Evapotranspiration deficits and yield reduction in hybrid RS626 for all gradient irrigations during 1978.

RS 626 requires about one week longer growing season than does NB 505 (Dreier, et al., 1979).

Another source of the variability in the yield relationship between these varieties may arise from differences in their rooting characteristics so that one variety may be a more efficient forager for water. Obviously, a method is needed to determine when differences in yield between varieties are due simply to environmental factors (availability of moisture in this case) or to genetic differences.

The crop yield data from this experiment are discussed in greater detail in Gilley et al. (1980) and Garrity (1980).

Relationship Between Crop Temperature and Grain Yield

The summation of the crop temperature differences between row 2 and other rows (ΣTSD) was examined for its relationship to grain yield in all irrigation treatments for NB 505 and RS 626 (Fig. 7). Although the two varieties yield differently the slopes of their response to ΣTSD are essentially the same. This finding has important implications for those who are attempting to assess the effects of drought on sorghum grain-yield reductions. If the yield potential in non-stressed conditions is known grain yield reductions might be estimated as a function of ΣTSD values.

One surprising result when crop temperature data are used as an index of stress is seen in a comparison of Figs. 5 and 7. Although the yield-ET relationship differs according to irrigation treatment, the yield-ΣTSD relationship appears to remain relatively constant between irrigation treatments. Thus, the large drop off in yield seen in the I-I-G treatment was associated with a large

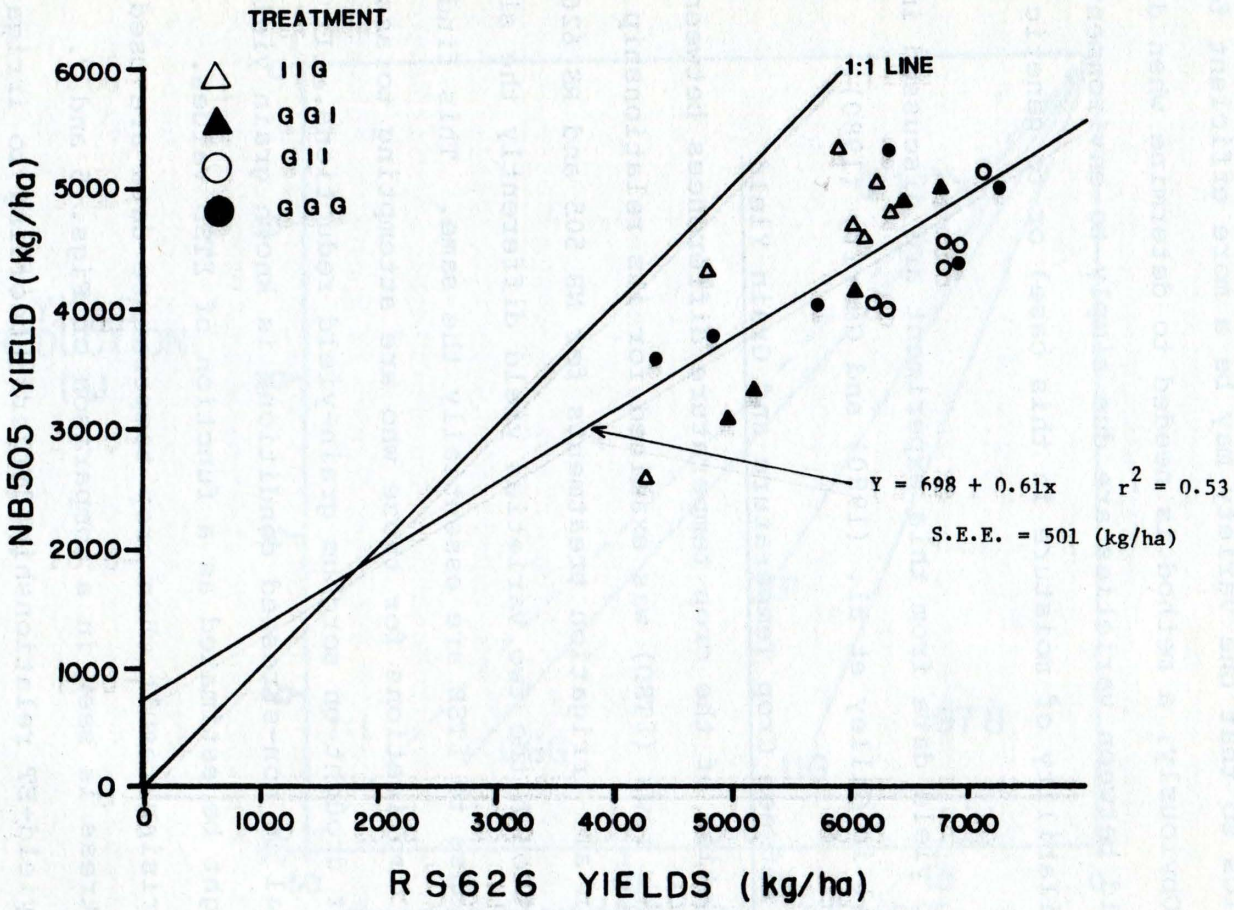


Fig. 6. Relationship between yields of RS626 and NB505 with similar irrigation treatments.

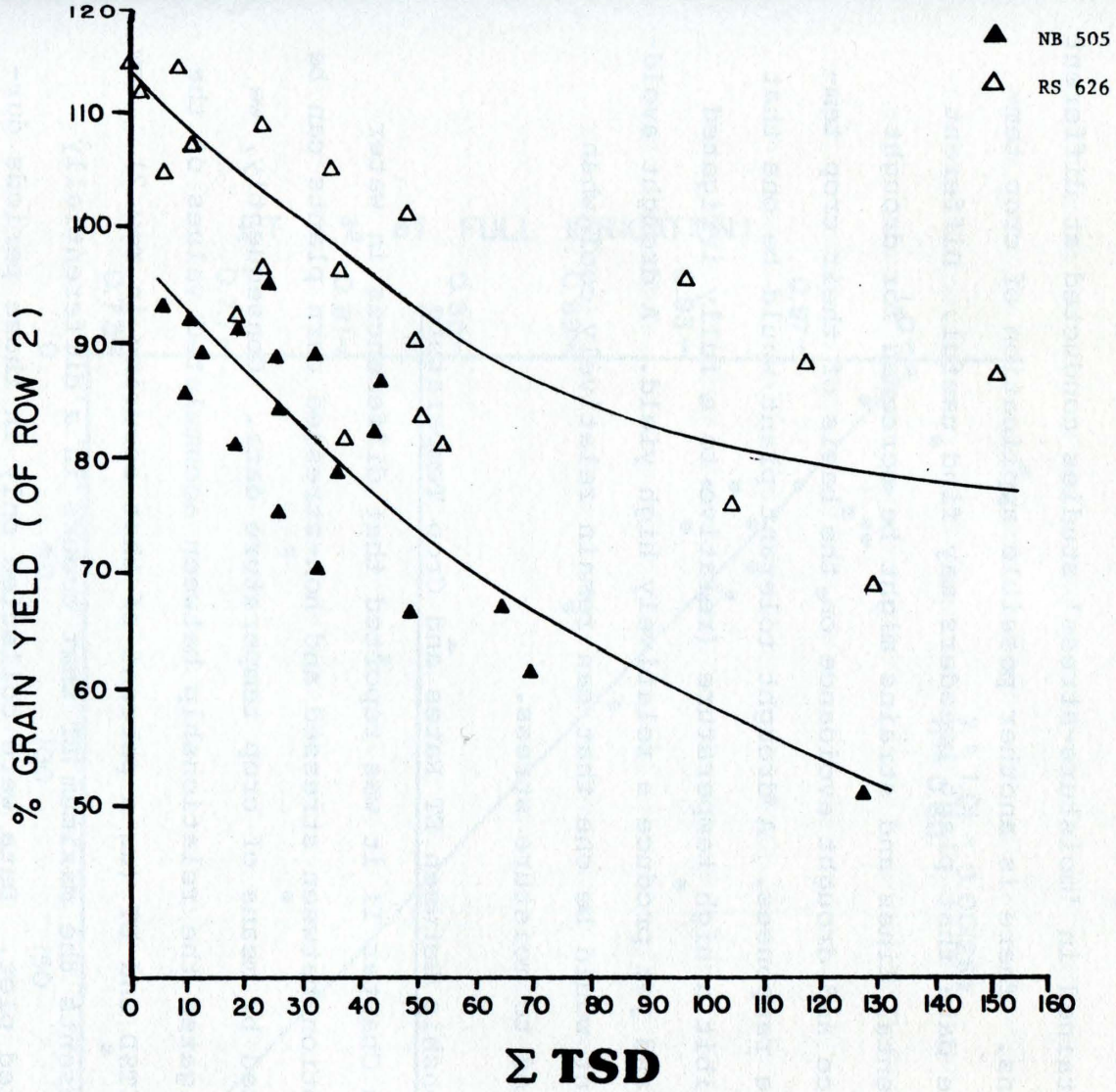


Fig. 7. Percent reduction in grain-yields as a function of ΣTSD for sorghum hybrids RS626 and NB505. Data were obtained in 1978.

increase in crop temperature of stressed plants during the G treatment.

Our results lead us to conclude that crop temperature measurements should provide an effective means for comparing yield data obtained in 'moisture-stress' studies conducted at different locations. There is another possible application of crop temperature data that plant breeders may find useful. Different experimental lines and strains might be screened for drought tolerance and drought avoidance on the basis of their crop temperature responses. A drought tolerant plant would be one that can exhibit a high temperature (relative to a fully irrigated plant) and yet produce a relatively high yield. A drought avoidant plant would be one that can remain relatively cool when subjected to moisture stress.

Relationship Between ET Rates and Crop Temperature

In Chapter II it was reported that differences in water consumption between stressed and non-stressed corn plants can be estimated by means of crop temperature data. Consequently, we investigated the relationship between accumulated values of the index ΣTSD and ET (as a percent of that occuring in row 2). Row 2 represents the maximum ET that occurs in a differentially irrigated plot. Data were collected only in those periods during which a plot was subjected to a "G" treatment.

The correlation between increased crop temperature and decreased ET was relatively low ($R^2 = 0.60$) (Fig. 8). One factor which may contribute to the variability of the data is the relatively small number of samples available for statistical analysis.

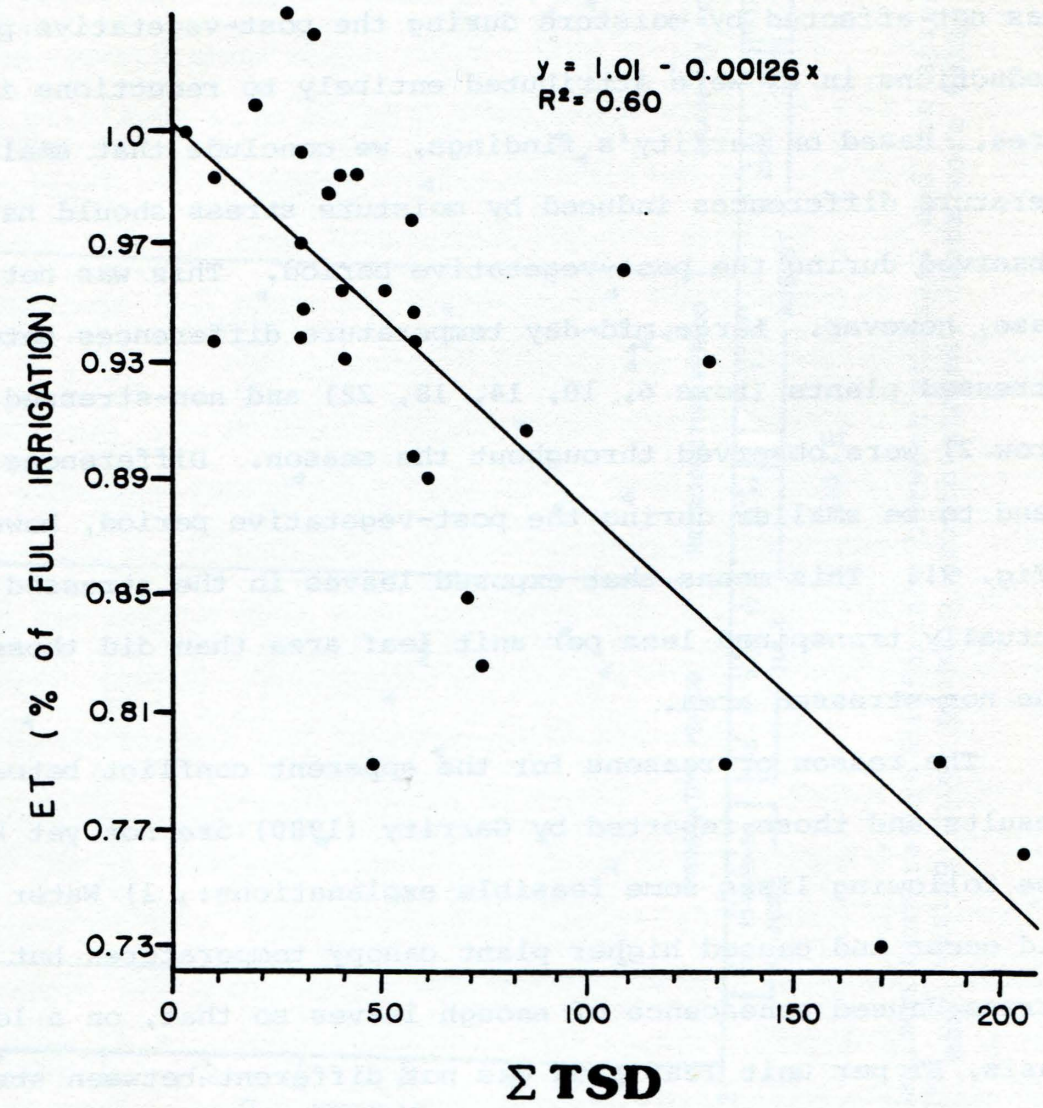


Fig. 8. Percent reduction in evapotranspiration (ET) as a function of cumulative canopy temperature difference (ΣTSD) between well-watered and stressed sorghum plants.

It is also likely that inaccuracies in estimating ET using the soil water balance method contribute to the variance.

Garrity (1980) found evidence that sorghum plants used in this study lost stomatal control after the vegetative period. He also reported that the average canopy (ET) per unit leaf area was not affected by moisture during the post-vegetative period. Reductions in ET were attributed entirely to reductions in leaf area. Based on Garrity's findings, we conclude that small temperature differences induced by moisture stress should have been observed during the post-vegetative period. This was not the case, however. Large mid-day temperature differences between stressed plants (rows 6, 10, 14, 18, 22) and non-stressed plants (row 2) were observed throughout the season. Differences did tend to be smaller during the post-vegetative period, however, (Fig. 9). This means that exposed leaves in the stressed areas actually transpired less per unit leaf area than did those in the non-stressed area.

The reason or reasons for the apparent conflict between our results and those reported by Garrity (1980) are not yet known. The following lists some feasible explanations: 1) Water stress did occur and caused higher plant canopy temperatures but the stress caused senescence of enough leaves so that, on a long term basis, ET per unit leaf area was not different between stressed and non-stressed plants; 2) Plant water stress occured during so short a time each day that total ET was affected only to a minor degree; 3) Because of reduction in the amount of leaf area in the stressed plots, the IRT may have viewed warm soil background thereby raising the apparent plant canopy temperature; 4) The

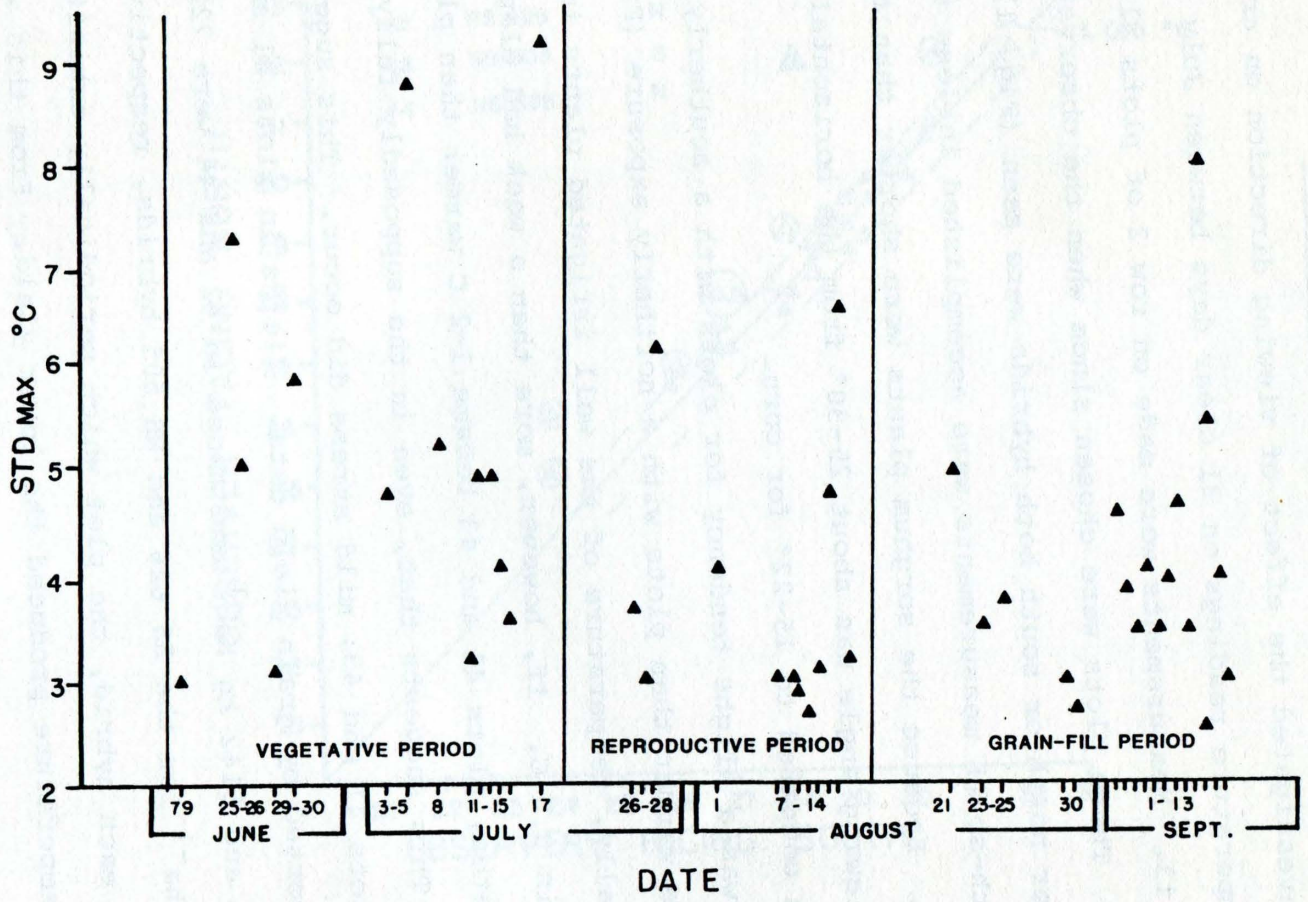


Fig. 9. Maximum temperature difference between stressed and non-stressed sorghum (STD_{max}) during three primary growth stages. Data were taken during 1978.

differences are due to measurement errors.

Application of Infrared Thermometry to Irrigation

We investigated the effect of viewing direction on crop canopy temperature readings on 21 clear days between July 24 and September 13. Measurements were made on row 2 of plots 41, 42, 43 and 44. These plots were chosen since when the observer faced either north or south both hybrids were seen (Fig. 1). A set of north-south measurements were accomplished in less than one minute. Because the sorghum plants were shorter than the corn the viewing angle was about 25-30° from the horizontal in the sorghum compared to 15-22° for corn.

There was a slight tendency for plots with a southerly exposure to be warmer than plots with a northerly exposure (Fig. 10). Generally, temperature of the well irrigated plants in row 2 were within 0.5 C. If, however, more than a week had elapsed since irrigaton, plots 41 and 43 became 1-2 C warmer than plots 42 and 44. This suggests that, even in the supposedly fully-irrigated plots 41 and 43, mild stress did occur. This suggestion is supported by grain yield data. Yields in plots 41 and 43 were 6733 and 5142 kg ha^{-1} and those in 42 and 44 were 7228 and 5388 kg ha^{-1} for the RS 626 and NB 505 hybrids, respectively. Thus, within each hybrid, the plot which periodically exhibited the warmer temperature produced the lower yield. From this we infer that sorghum yield is sensitive to moisture stress.

We conclude from these observations that crop temperature measurements provide a sensitive indicator of sorghum water stress and can be used to evaluate the efficiency of various irrigation

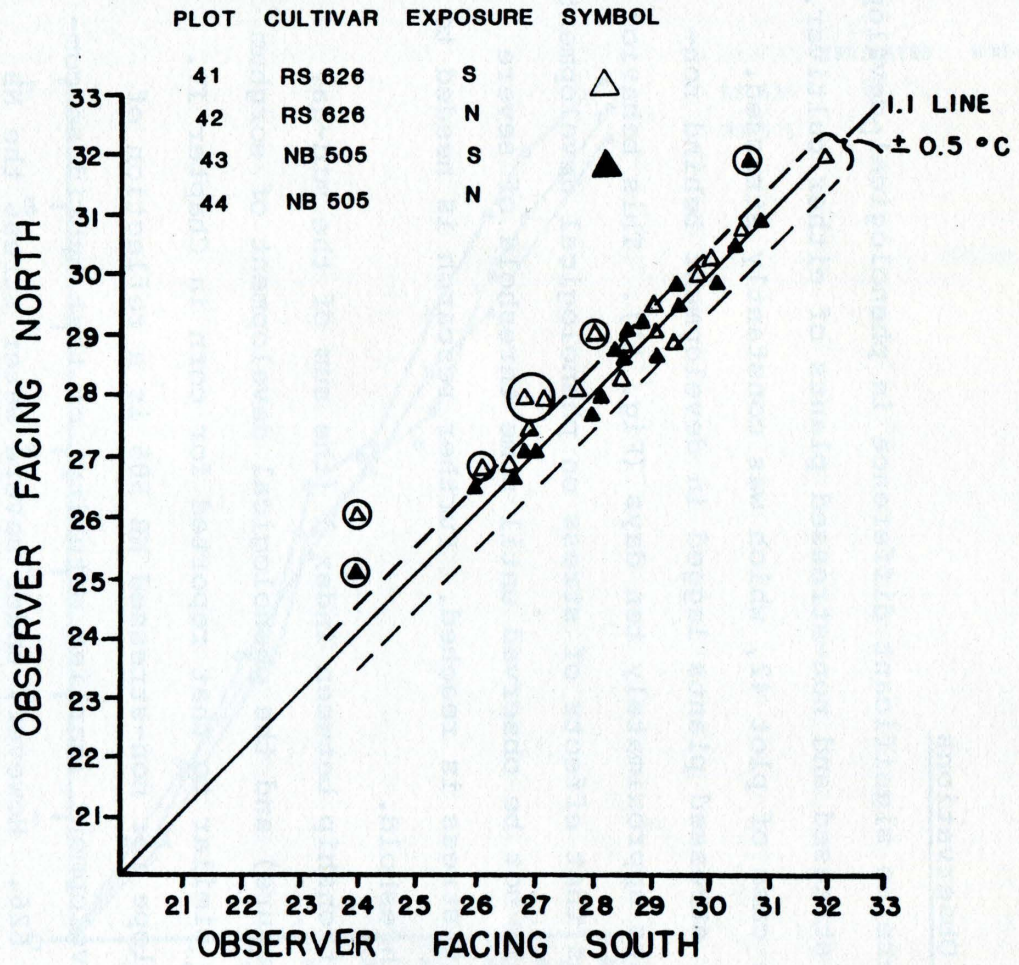


Fig. 10. Comparison of mid-day IRT temperatures of fully irrigated sorghum with the observer facing north and south on 21 clear days between July 24 and September 13, 1978, for two sorghum hybrids, RS626 and NB505.

scheduling techniques. Also on the basis of our results, it appears that if the crop temperature difference between two areas one of which is fully-irrigated, exceeds about 0.5 C, the need for irrigation of the warmer plot is indicated.

Phenological Observations

There were no significant difference in phenological development between stressed and non-stressed plants of either cultivar, except in the case of plot 42, which was constantly stressed. In this plot, stressed plants lagged in development behind non-stressed plants approximately ten days (Fig. 11). This behavior suggests to us that effects of stress on phenological development in sorghum will not be observed until some threshold of severe and persistent stress is reached. Further research is needed to define this threshold.

The relationship between index 1 (the sum of the mid-day canopy temperature) and the phenological development of sorghum (Fig. 12) was similar to that reported for corn in Chapter IV. The steeper slope for non-stressed NB 505 is a reflection of more rapid development (earlier maturity) of that hybrid as compared with RS 626. However, under severe water stress the NB 505 may be expected to mature later than would than non-stressed RS 626. These results provide further evidence that phenological development may be monitored by methods involving remote sensing.

Relationship Between Leaf Water Potential and Temperature Stress

The relationship between differences in mid-day leaf water potential ($\Delta\psi_\ell$) and difference in canopy temperature between stressed and non-stressed plants (ΔT) was studied on eleven clear

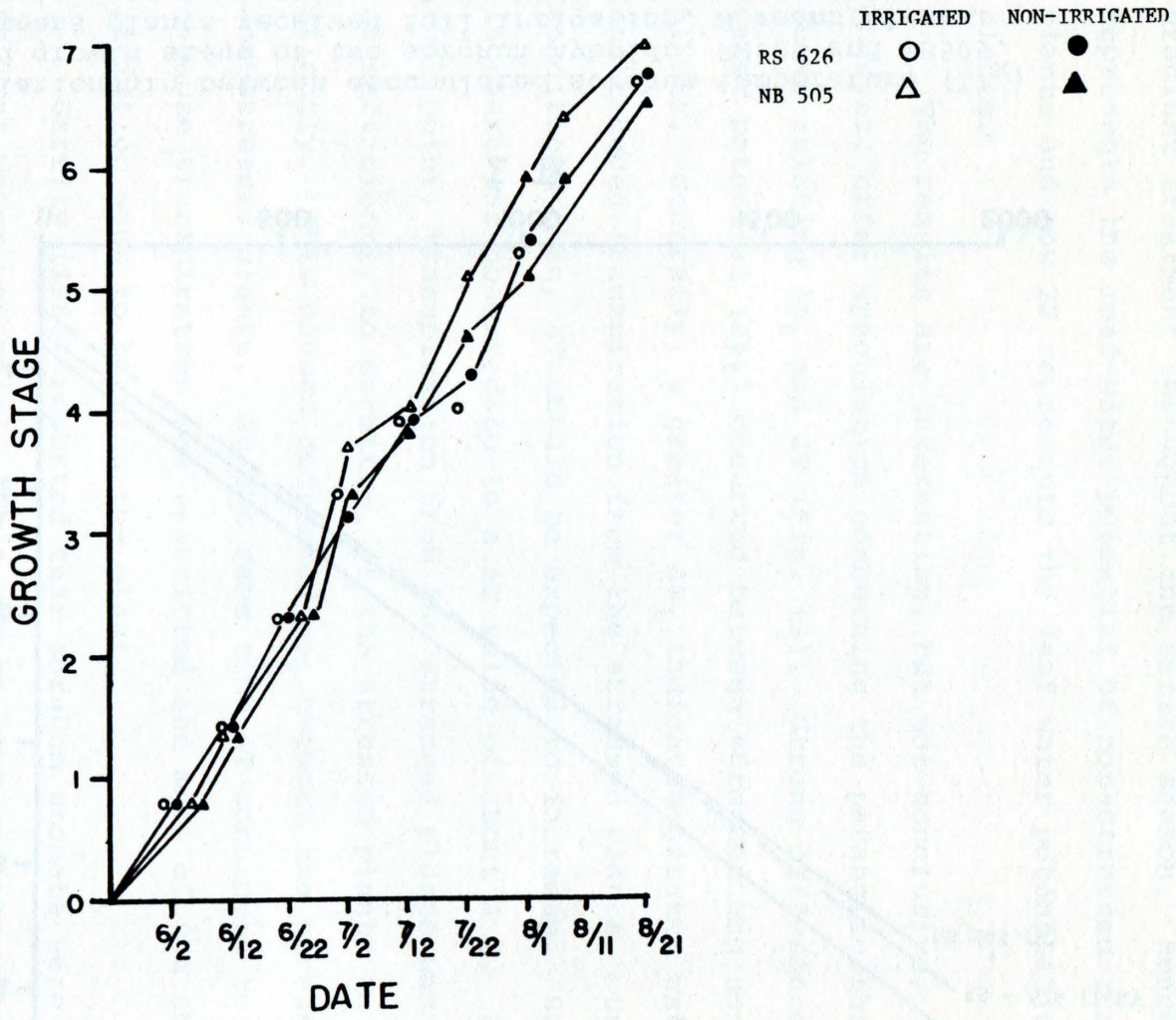


Fig. 11. Growth stages of two sorghum hybrids, RS626 and NB505, as influenced by water stress due to different irrigation treatment. Data obtained in 1978.

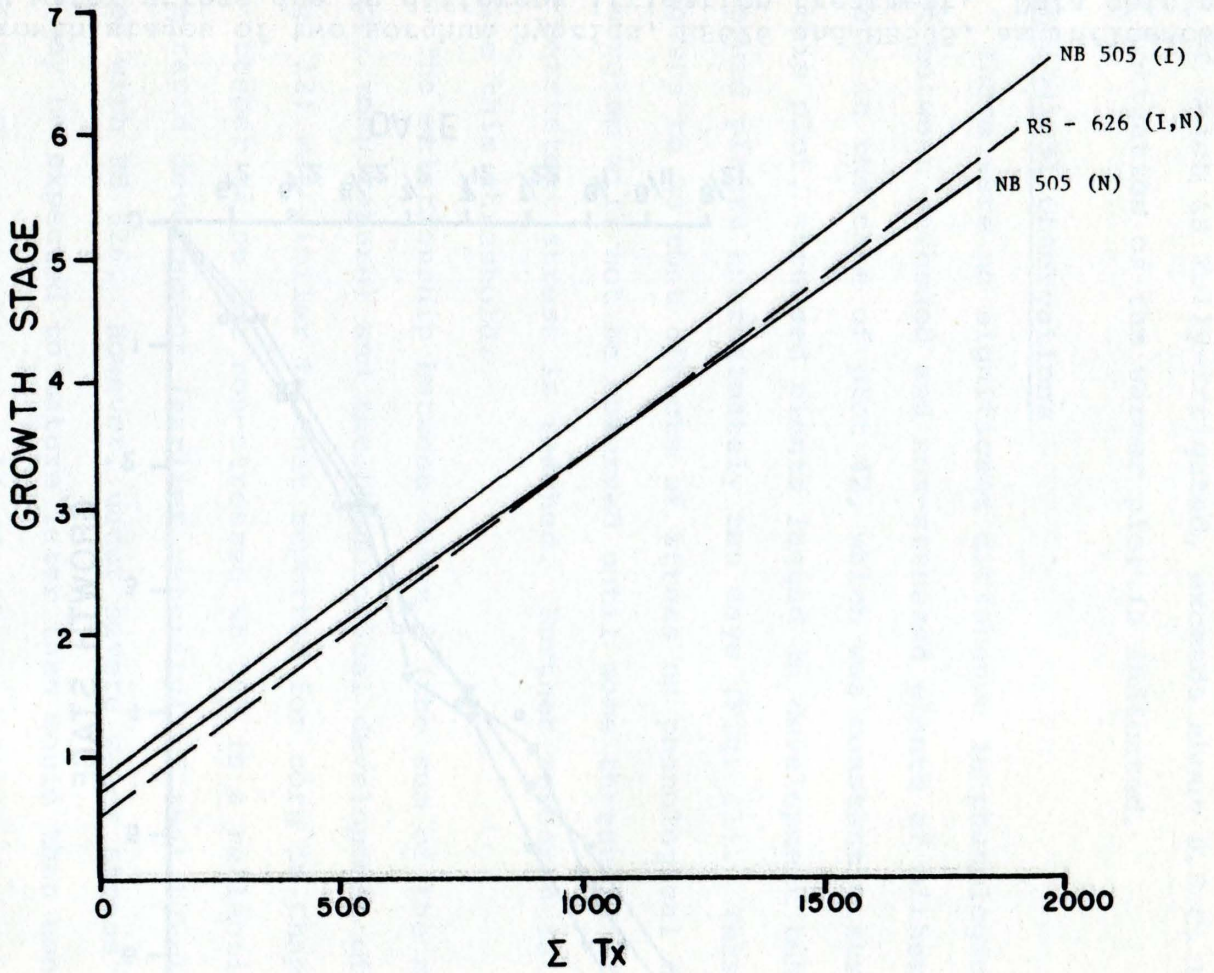


Fig. 12. Relationship between accumulated sorghum temperature (ΣT_x) and growth stage of two sorghum hybrids, RS626 and NB505. I means plants received full irrigation, N means plants received no irrigation. Data were obtained in 1978.

days between July 28 and September 4 (Fig. 13). Plot 42 was selected for this purpose since it was subjected to a moisture gradient treatment throughout the entire season. Hence, row 2 represents the leaf-water potential of non-stressed irrigated plants and row 22 represents the leaf water potential of dryland plants.

The results are interesting, but not conclusive. We can, however, offer speculation concerning the parabolic shape of the curve relating $\Delta\psi_\ell$ and ΔT (Fig. 13). Strong differences in leaf water potential ($\Delta\psi_\ell$) occurred between stressed and non-stressed plants. Generally, a greater $\Delta\psi_\ell$ indicates greater water stress and reduced transpiration from the stressed plants. Under such conditions then, ΔT should be expected to increase. Such an increase was observed up to a ΔT value of about 4 C. Beyond that point, transpiration from the stressed plants was restricted sufficiently to permit ψ_ℓ of the stressed plants to increase slightly. This caused decreased $\Delta\psi_\ell$ between the stressed and non-stressed plants. At the same time ΔT continued to increase because transpiration was restricted and more of the absorbed radiation went to heating the plant.

Garrity (1980) reported that sorghum stomata were insensitive to leaf water potential. This may be true - up to some critical level of stress. Once such a threshold is passed, however, stomates probably close. If stomates remain closed, whether by some chemical inhibitor or because of some other physiological effect, such mid-day ΔT values as we observe are possible. It may take from one to five days for the stomata to fully reopen once stress is removed (Hsiao, 1973). During this period of

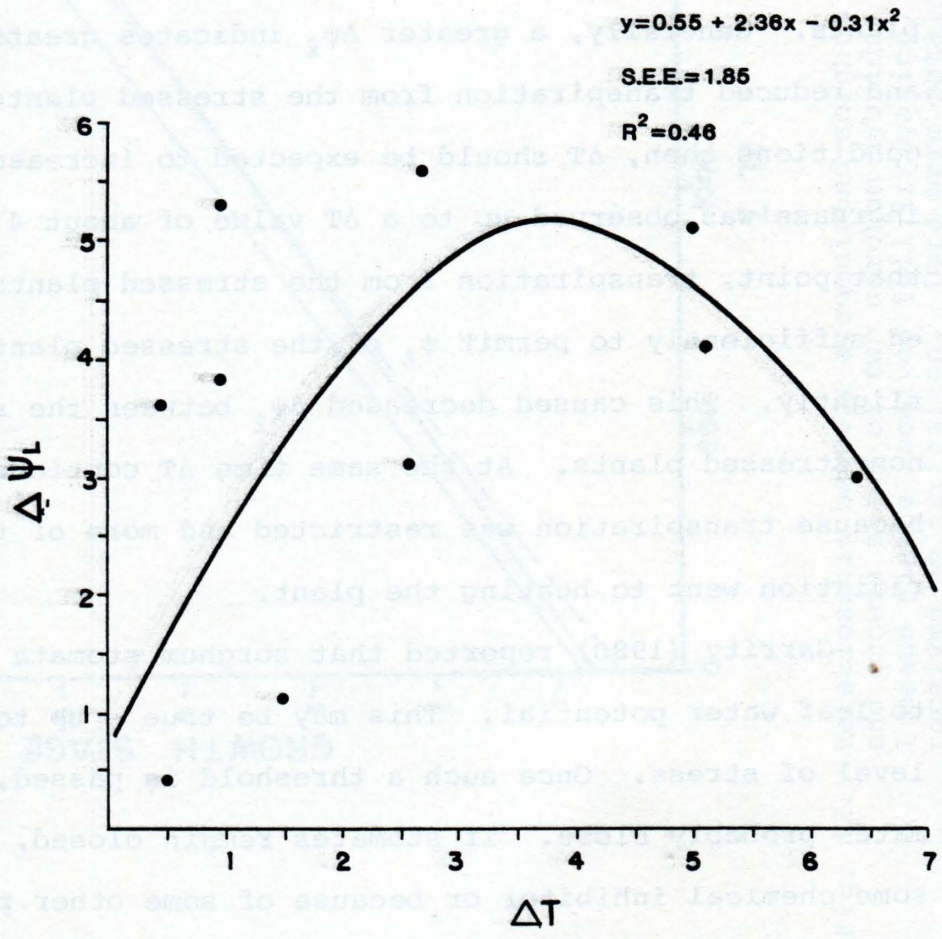


Fig. 13. Relationship between the difference in leaf water potential ($\Delta\psi_\ell$) and the difference in crop temperature (ΔT) between water-stressed and non-stressed sorghum hybrid RS626. Data obtained in 1973.

stomatal closure, $\Delta\psi_\ell$ would become smaller even though ΔT would continue to increase. The parabolic response shown in Fig. 13 is consistent with this suggestion. We expect to see this response only on severely stressed plants under high atmospheric demand situations.

Assuming that we are correct, an interesting problem arises in attempting to measure and evaluate stress on the basis of ψ_ℓ and crop temperature measurements. If $\Delta\psi_\ell$ is small, one might assume that actually stressed plants are non-stressed plants. But what if, at the same time, the stomata are closed? Then, ΔT will be positive in sign. More importantly, the stressed plant will not be photosynthesizing. Hence, the yield potential of the plant is reduced in spite of the lack of apparent water potential deficits. Thus, ΔT measurements may more accurately reflect the occurrence of plant stress than will $\Delta\psi_\ell$ measurements. More study is required, however, to establish the validity of the relationships between $\Delta\psi_\ell$ and ΔT that we observed. If the relationship can be established, research should follow to understand the mechanisms involved.

REFERENCES

Bartholic, J. F., L. N. Namken and C. L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. Agron. J. 64:603-608.

Castleberry, R. M. 1973. Effects of thinning at different growth stages on morphology and yield of grain sorghum (S. bicolor L. Moench). Ph.D. dissertation, Univ. of Nebraska-Lincoln.

Drier, A. F., P. T. Nordquist, L. V. Svec, P. H. Grabouski, and L. A. Nelson. 1979. Nebraska Grain Sorghum Performance Tests. E. C. 80-106. Cooperative Extension Service, Institute of Agriculture and Natural Resources, Univ. of Nebraska.

Gardner, B. R. and B. L. Blad. 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. Agricultural Meteorology Progress Report 80-1. Center for Agricultural Meteorology and Climatology, Univ. of Nebraska-Lincoln.

Garrity, D. P. 1980. Moisture deficits and grain sorghum performance, limited irrigation strategies, evapotranspiration relationships, stress conditioning and physiological responses. Ph.D. dissertation, Univ. of Nebraska-Lincoln.

Gilley, J. R., D. G. Watts and C. Y. Sullivan. 1980. Management of irrigation agriculture with a limited water and energy supply. Old West Regional Commission Report. Grant No. 10670259.

Hsiao, T. C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Idso, S. B., R. J. Reginato and R. D. Jackson. 1977. Remote sensing of crop yields. Science 196:19-25.

Inuyama, S., J. T. Masick, D. A. Dusek. 1976. Effect of plant water deficits at various growth stages on growth, grain yield and leaf water potential of irrigated grain sorghum. Proc. Crop Sci. Japan 45(2):298-307.

Jensen, M. I. and W. H. Sletten. 1957. Good irrigation management brings increased sorghum yields. Soil and Water, July, pp. 8-9.

Millar, A. A., R. E. Jensen, A. Bauer and E. B. Norum. 1971. Influence of atmospheric and soil environmental parameters on the diurnal fluctuations of leaf water status of barley. Agric. Meteorol. 8:93-105.

Palmer, J. H. 1965. Diurnal variation in leaf and boll temperatures of irrigated cotton grown under two soil moisture regimes in a semi-arid climate. Agric. Meteorol. 4:39-54.

Stewart, J. I., R. D. Misra, W. D. Pruitt and R. M. Hagan. 1975. Irrigating corn and grain sorghum with a deficient water supply. Trans. Amer. Soc. Agr. Engr. 18(2):270-279.

Sumayao, C. R., E. T. Kanemasu and T. Hodges. 1977. Soil moisture effects on transpiration and net carbon dioxide exchange of sorghum. Agric. Meteorol. 18:401-408.

Vanderlip, R. 1972. How a sorghum plant develops. Kansas State Univ., Manhattan, Cooperative Extension Service Circ. C-447.

Wiegand, C. L. and L. N. Namken. 1966. Influences of plant moisture stress, solar radiation and air temperatures on cotton leaf temperature. Agron. J. 58:582-586.

CHAPTER VII

SCHEDULING CORN IRRIGATION BY UTILIZING INFRARED THERMOMETRY

K. L. Clawson and B. L. Blad

ABSTRACT

Irrigation scheduling is an increasingly important practice in the management of valuable water resources in agricultural regions where natural precipitation is supplemented by irrigation. The study reported here was aimed at evaluating the feasibility of scheduling irrigation in corn (Zea mays L.) using canopy temperature data obtained with a hand-held infrared thermometer (IRT).

Specific objectives of the study were 1) to determine if irrigation scheduling can be done using data on crop canopy temperature and, 2) to evaluate the effectiveness of a number of canopy temperature irrigation scheduling methods based on canopy temperature measurements in terms of plant responses and soil water balance.

The range in temperature of six readings made with an IRT - defined as the canopy temperature variability (CTV) - of a fully irrigated reference plot (WW) was less than 0.7 C. As the temperature difference between a stressed plot and the WW plot increased so did CTV values. This was true until a certain stress level was reached at which point CTV values leveled off. The onset of stress can, therefore, be identified when CTV exceeds 0.7 C but, it appears, that the temperature difference between well-watered and stressed vegetation provides a better measure of stress severity than do CTV values.

Two kinds of irrigation initiating procedures were studied.

In one procedure irrigation is initiated when the range of six measurements in a plot reached 0.8 C (0.8 CTV). The second procedure consists of a comparison of the difference between the average canopy temperatures of the WW plot and of the plot to be scheduled. Irrigation was initiated when plot temperatures became either 1.0 (1SMW) or 3.0 C (3SMW) warmer than the well-watered plot. At least two irrigations were called for in each plot scheduled on the basis of temperature.

A total of 26 cm of water was applied to the well-watered plot while the 0.8 CTV plot received only 12 cm. By the end of the growing season almost all available water had been extracted from soil in the temperature scheduled plots but the soil profile was still almost full in the well-watered plot. This suggests that soil water was more effectively used during the growing season in the temperature scheduled plots.

Grain yields (Y) were reduced in the order of increasing water stress as follows:

$$Y_{WW} > Y_{0.8CTV} > Y_{1SMW} > Y_{3SMW} > Y_{DL}$$

Compared to the well-watered plot, yields of grain in the CTV treatment were reduced by about 5% but not significantly so, with respect to the well-watered plot. Grain yields in the other temperature scheduled plots were significantly reduced below the yields of the well-watered plot, but only about 5 to 6 cm of irrigation was applied.

INTRODUCTION

Irrigation scheduling has become important in water management schemes for cultivated lands in subhumid, semiarid and arid

regions. It has been suggested that crop temperature measurements may be used to schedule irrigations. Tanner (1963) was among the first to use infrared thermometry to measure canopy temperature differences caused by water stress. He found a maximum temperature difference of 3 C between irrigated and unirrigated potatoes (Solanum tuberosum). Increases in temperature appeared to be due to an observed stomatal closure.

Increases in canopy temperature have been correlated with leaf relative turgidity (Wiegand and Namken, 1966), soil water content (Millar, et al. 1971 and Bartholic, et al. 1972) and leaf water potential (Erhler, et al. 1978 a, b).

Heermann and Duke (1978) reported a linear relationship between grain yields of corn and increases in canopy temperature due to stress. They observed that grain yields did not begin to decline until the average growing season temperature of the stressed plants exceeded the temperature of well-watered plants by 1.5 C. Every additional degree rise reduced yields by 15%. These relationships were obtained from temperature measurements made with an infrared thermometer held in a vertical position over the crop. When the IRT was held at an oblique angle, the numerical relationships changed slightly.

Gardner (1980) correlated corn yields with differences in canopy temperature between stressed and non-stressed plants grown under several irrigation regimes. Summation of these mid-day differences in daily temperature during the pollination and grainfill stages was used successfully to predict grain yield to within 10% of actual values.

Aston and van Bavel (1972) suggested that the onset of water

deficit conditions could be detected by comparing the canopy temperature of a stressed plot with that of a well-watered reference plot. They also theorized that a field might serve as its own reference because of differing soil water contents due to non-uniform irrigation application and infiltration rate. Because of such inhomogeneity, they suggested, the variability in crop temperature measured at several locations within the same field may indicate the onset of water stress.

Millard et al. (1978) found canopy temperature variability in a wheat field, 72 m x 15 m in size, as detected by an airborne thermal scanner, was as great as 5 C. They cautioned that spot measurements of canopy temperatures made near the ground may not be indicative of overall field conditions. According to Nixon et al. (1973) the practice of using average canopy temperature of water-stressed plots above that of non-stressed plots in order to characterize water stress is not strictly valid. This is because of the variations in canopy temperature that occur within a field. They observed that the canopy temperature variability within an 800 m wide field of cotton increased as soil water was depleted, although an elevation in average canopy temperature was not detected. They suggested that canopy temperature variability indicated the presence of spots with adequate or inadequate water in a field. This temperature variability, therefore, could be used in irrigation management.

In Chapter V it was reported that in fully irrigated plots of corn the standard deviation of mid-day canopy temperatures was about 0.3 C. In non-irrigated plots, it was as great as 4.2 C. We concluded that plots which exhibited an increase in the stan-

dard deviation above 0.3 C indicated were in need of irrigation.

The objectives of the study reported here were 1) to determine whether irrigation can be effectively scheduled using canopy temperature data obtained with a handheld infrared thermometer (IRT) and 2) to evaluate the influence of irrigations so scheduled on plant growth and on soil water balance.

MATERIALS AND METHODS

This study was conducted during the summer of 1979 in the solid set irrigation area at the Sandhills Agricultural Laboratory. The Laboratory is located 40 miles north of North Platte, near Tryon in McPhearson County, Nebraska (41° 37' N, 100° 50' W, 975 m above m.s.l.). The soil has been tentatively classified as Valentine fine sand, loamy substratum phase (order Entisol). It is characterized by a sandy surface with buried clay horizons. These horizons may have water holding capacities 3.5 times as great as the overlying sand (Lewis, 1976).

Five plots were planted to corn (cv Pioneer 3901) on May 19 in 76 cm wide N-S rows at a rate of 69,190 plants per hectare. Plots were later thinned to 64,250 plants per hectare. Each plot measured 28.3 m E-W by 56.6 m N-S (Fig. 1). A 9 m wide grass strip bordered the plots to the west. The area bordering the other three sides of the experimental area was planted to corn which was fully irrigated during the entire season. Each plot was irrigated with sprinklers about 2 m above the ground and spaced 18.9 m apart N-S on the borders. A small path about 3 m in width was left between the center of the plots to allow for access to instrumentation.

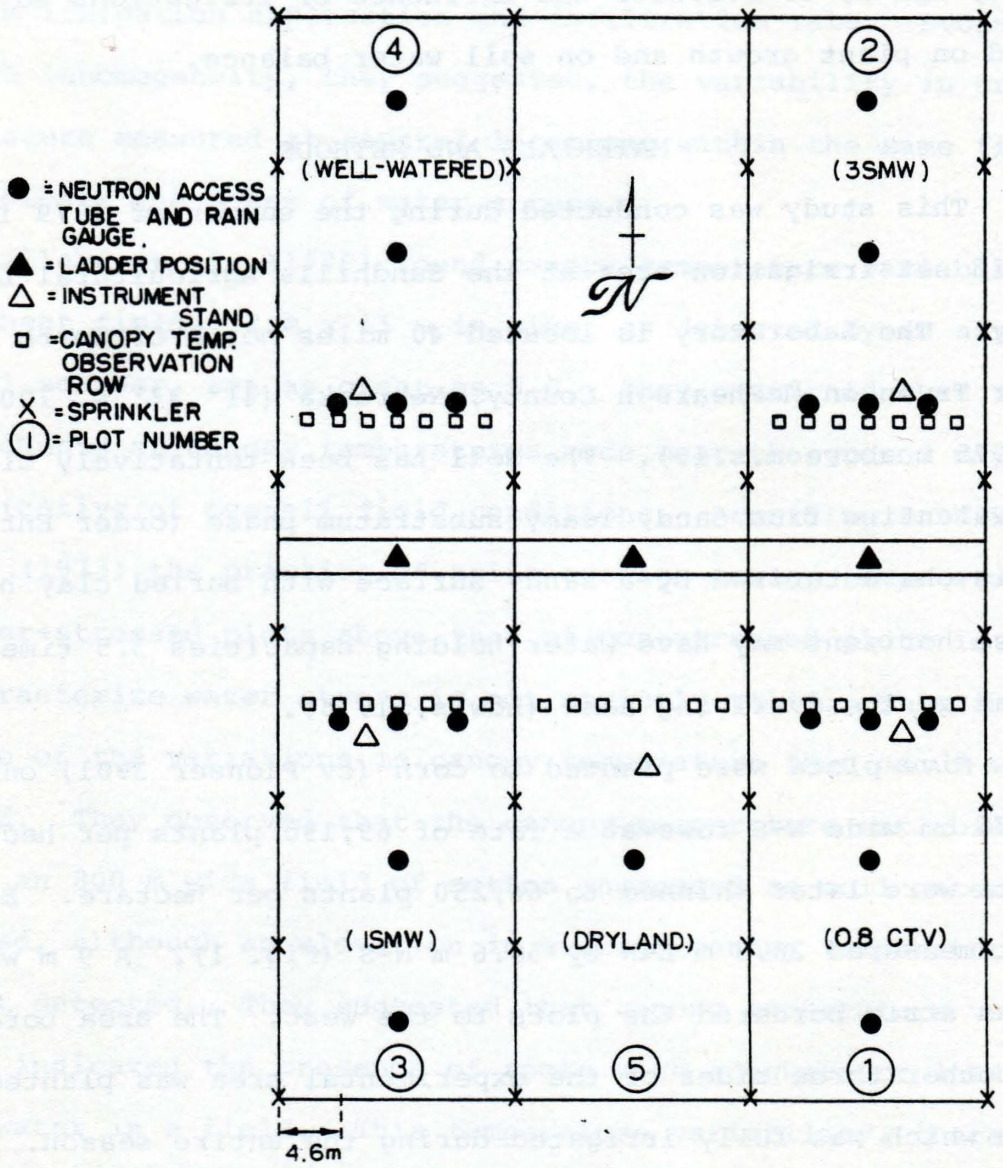


Fig. 1. Detail of the five experimental plots at the University of Nebraska Sandhills Agricultural Laboratory.

Plots were harvested on October 19 for grain yield comparisons. Ten rows were selected for harvest in each plot. Seven of these included the rows in which infrared measurements had been made. Harvest rows were 5.9 m in length. Ears were harvested by hand and shelled mechanically.

During the season canopy temperatures were measured with a handheld infrared thermometer.[1] The instrument has a field of view of 5°, a sensing window of 10.5-12.5 μm, a resolution of 0.1 C, and a guaranteed accuracy of 0.5 C. The instrument was calibrated frequently using a method described by Blad and Rosenberg (1976). The output of the IRT agreed well with the temperature of a blackbody immersed in a controlled temperature water bath over a wide range of temperatures. The instrument performance was frequently checked by comparing the IRT reading to the temperature of a water bath.

Canopy temperature measurements began on July 11 and ended on September 15. Canopy cover was greater than 85% during this period. Seven spot measurements were made in each plot daily at about 1400 hours solar time. Measurements were made from atop a 4 meter portable ladder positioned in front of row 12 at the middle of each plot. The IRT was aimed consecutively at rows 3, 6, 9, 12, 15, 18 and 21. The reading from row 12 was discarded because the IRT "view" of that row included the exposed soil, leading, often, to excessively high temperature readings. At the other angles of view across the plot, canopy cover appeared to be 100% complete.

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[1]Telatemp Corp., P.O. Box 5160, Fullerton, CA (model AG-42).

The IRT was pointed in a southerly direction for observation of plots 1, 3 and 5. When observation of plots 2 and 4 were made, the IRT was pointed in a northerly direction. Differences in corn canopy temperature as a function of direction were small enough to be neglected (see Chapter IX and Fuchs et al., 1967). The area of vegetation viewed from the ladder was about 0.2 m^2 and was elliptical in shape. The major and minor axes were about 1 and 0.6 m, respectively.

The parameters chosen as irrigation initiators were designed to create a range of growing conditions from ample water supply to drought. Treatments are detailed in Fig. 1. Plot 5 was designated as a "dryland" control plot (DL) and received only naturally occurring rainfall. Plot 4 was designated as a "well-watered" control plot (WW). It was irrigated weekly to refill the soil reservior to field capacity. The amount of water applied at each weekly irrigation to plot WW was computed as the amount needed to return the soil to field capacity. Weekly irrigation requirements were not corrected for sprinkler application efficiency. Water was applied by sprinklers until rain gauge catch at the canopy top indicated that the gross irrigation requirement had been satisfied. Deep percolation was, thereby, avoided.

Irrigations of plots 1 through 3 were determined on the basis of on canopy temperatures sensed by the IRT. Irrigation scheduling techniques were designed to simulate the conditions under which a farmer might use an IRT.

Irrigation of plot 1 was initiated when the canopy temperature variability (CTV) within that plot was at least 0.8 C or

greater (0.8 CTV). CTV is defined as the range (maximum minus minimum) of all IRT sensed canopy temperatures within a plot during a measurement period.

Treatments for plots 2 and 3 were based on comparison of the average canopy temperature of these plots with the average canopy temperature of the well-watered plot (plot 4). The average canopy temperature was computed by averaging all IRT sensed canopy temperature measurements in a single plot. Irrigation water was applied when the average canopy temperatures of plots 3 and 2 became, respectively, 1.0 and 3.0 C warmer than the average canopy temperature of plot 4. These treatments were termed 1SMW and 3SMW. SMW (Stressed Minus Watered) is defined as the difference between the average canopy temperature of a water stressed plot and that of a well-watered plot. The amount of water applied to each temperature scheduled plot ranged from 1.0 to 3.0 cm but was never greater than the weekly evapotranspiration (ET) from plot 4.

Soil water status was determined with a neutron moisture probe[2] on a weekly basis and more frequently as circumstances permitted. Five access tubes were installed to a depth of 1.52 m in each of plots 1 through 4. Plot 5 had only one access tube (see Fig. 1 for location of access tubes). Sampling depth increments for neutron probe measurements were 0-23, 23-46, 46-76, 76-107, 107-137, 137-168 cm. At at each access tube, two one-minute standard count readings were taken and two fifteen-second readings were taken at each depth.

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[2]Troxler Electronic Laboratory, Inc., Raleigh, NC (model 2651).

RESULTS AND DISCUSSION

The need for irrigation was indicated at least twice in each of the temperature scheduled treatments. The dates of each irrigation and the amounts of water applied are given in Table 1. The daily values of canopy temperature variability from the CTV scheduled plot are shown in Fig. 2. The temperature differences between the stressed and well-watered plots for the 1SMW and the 3SMW plots are shown in Figs. 3 and 4, respectively. All data plotted are for clear days after canopy cover became 85% complete.

The CTV plot received 12.7 cm of water in five separate applications during each of the three major stages of phenological growth. The threshold temperature of 1.0 C was not reached in the 1SMW plot until the pollination stage. That plot received a total of 5.4 cm of irrigation water - 2.6 cm in a single application in the pollination stage and 2.8 cm more from two applications during the grainfill stage.

The 3SMW plot was irrigated in all stages of growth although threshold canopy temperatures indicated the need for irrigation only twice. The 3SMW plot was unintentionally irrigated on July 3 and again on August 3. Irrigations were scheduled on the basis of canopy temperature parameters during the grainfill period on August 12 and 24. A total 6.2 cm of irrigation water was applied to the 3SMW plot.

The CTV and SMW temperatures were reduced in all cases following irrigation. CTV in the 0.8 CTV plot was reduced from greater than 0.8 C to a value between 0.5 and 0.7 C. CTV in the well-watered plot did not depend upon irrigation. For example, following an irrigation during the pollination period, CTV

Table 1. Dates of irrigation and amounts of water applied to each plot.

	Irrigation Treatment				
Dates	WW (cm)	0.8CTV (cm)	1SMW (cm)	3SMW (cm)	DL (cm)
July 3				1.2	
July 13	3.3				
July 15		3.2			
July 25	5.4	4.8			
August 3				3.7	
August 4			2.6		
August 7	6.1	2.6			
August 11		1.0	1.2		
August 12				1.5	
August 14	4.2				
August 22	6.4				
August 23			1.6		
August 24		1.1		1.0	
September 6	2.9				
Water Applied					
irrigation	28.2	12.7	5.5	6.2	--
rainfall	27.5	27.5	27.5	27.5	27.5
total	55.7	40.2	33.0	33.7	27.5

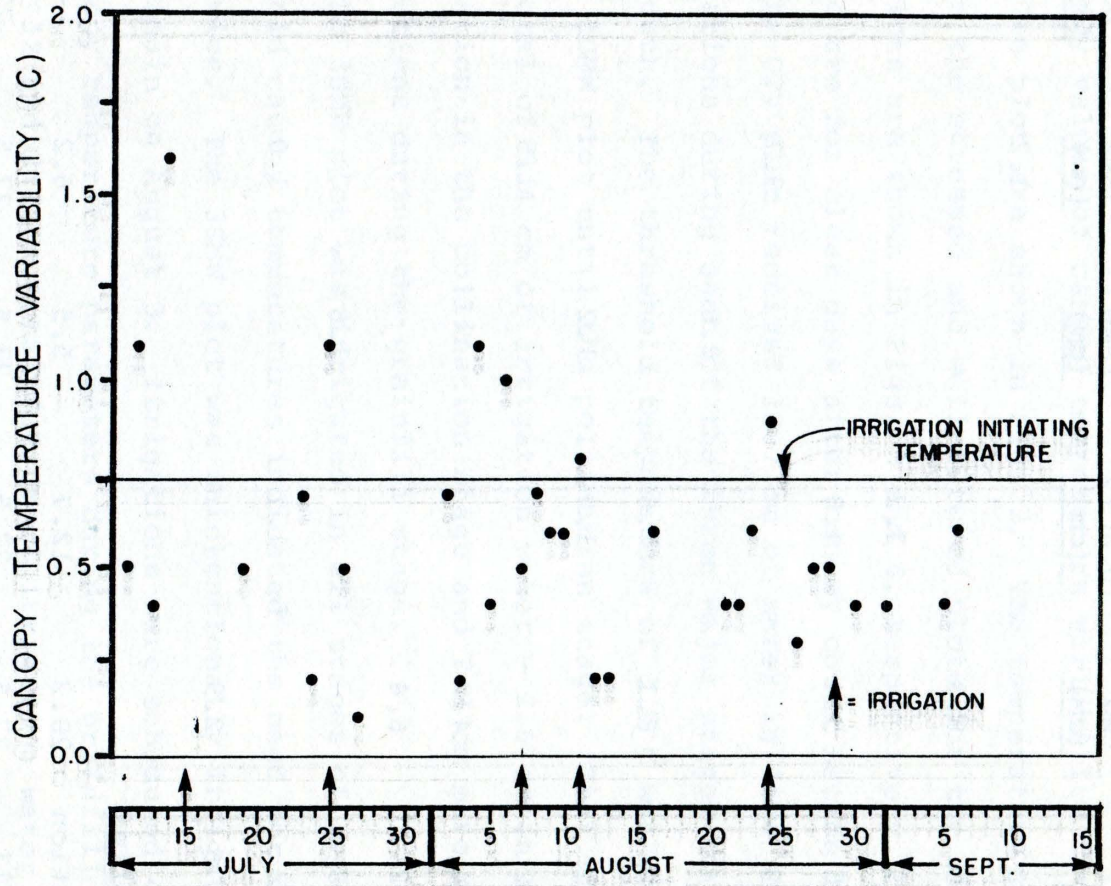


Fig. 2. Canopy temperature variability for the CTV plot throughout the growing season.

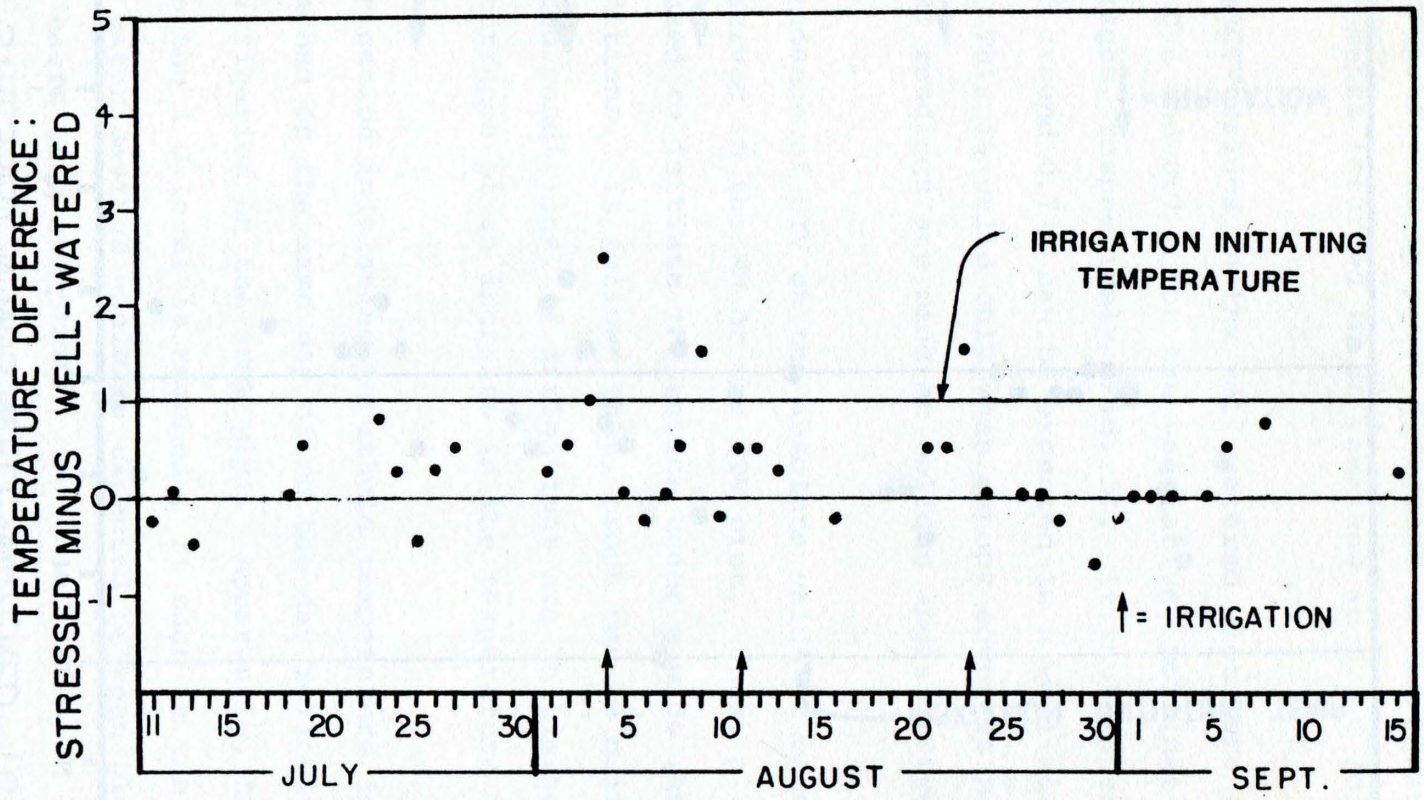


Fig. 3. Canopy temperature differences between the 1SMW plot and the well-watered plot.

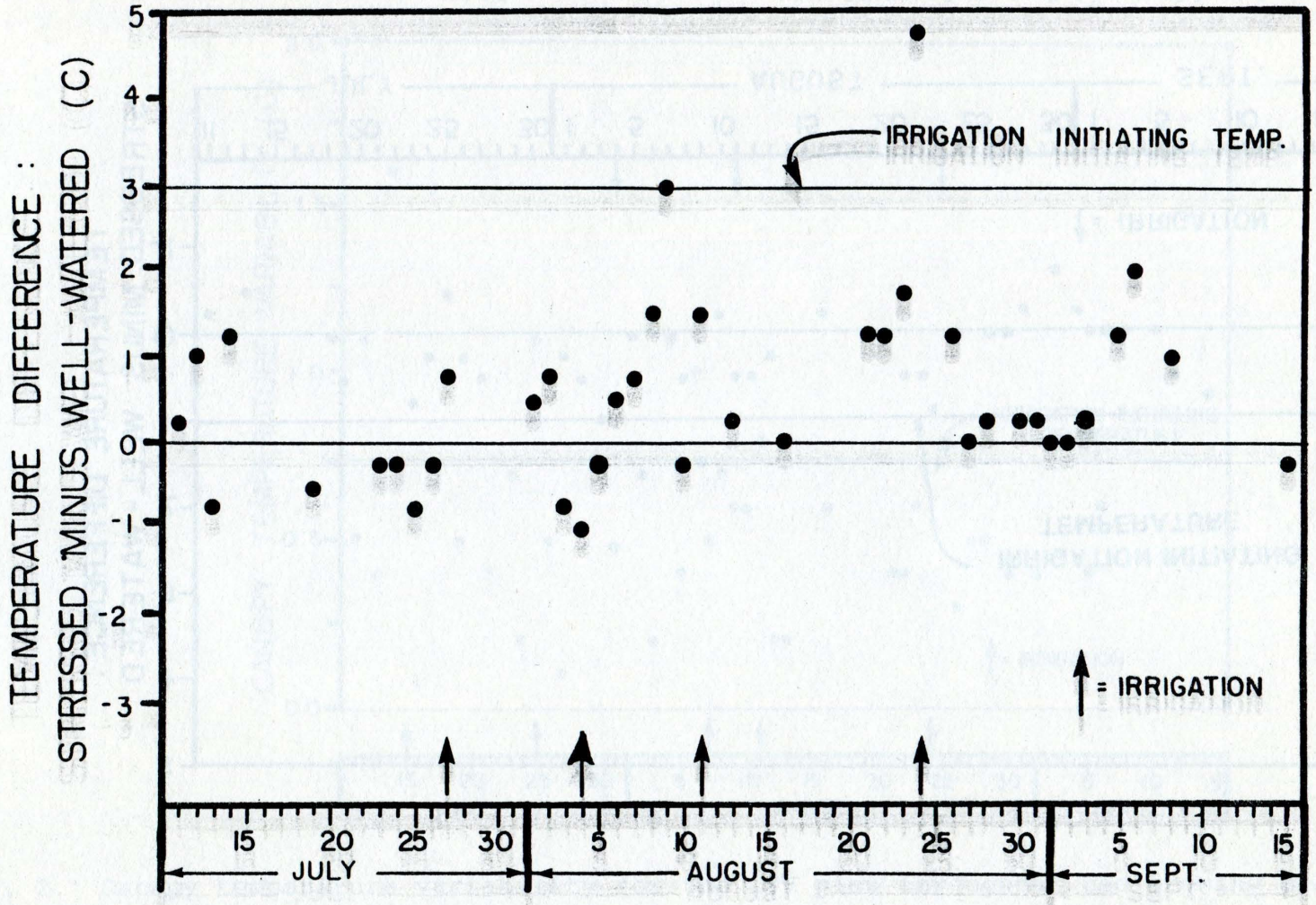


Fig. 4. As in Fig. 3 for the 3SMW plot.

remained at about 0.7 C. These results agree quite well with those of Gardner (1980) who reported that the standard deviation of mid-day canopy temperatures in plots scheduled on the basis of neutron probe measurements returned to or remained at 0.3 C following an irrigation.

Maximum CTV values in the well-watered plot were approximately 1.0, 0.6 and 0.7 C for the vegetative, pollination and grainfill stages, respectively (Fig. 5). It thus appears that a CTV value of around 0.7 C can be expected in a well-watered crop at mid-day. This is valid only when canopy cover is nearly complete and IRT readings are made at oblique angles between about 20° to 40°.

No dependence of CTV on the absolute value of canopy temperature was observed in the WW or the CTV plot. Thus, a specified CTV can be used to initiate irrigation under a wide range of weather conditions. It follows that, crops can be maintained in a well-watered conditions, if irrigations are initiated immediately after occurrence of an increase in the temperature variability above 0.7 C.

The irrigation initiating threshold temperature for the 3SMW plot was reached on the same day or on the day following the initiation of irrigation on the 1SMW plot. Apparently, SMW increases rapidly once the 1 C level is reached. If such is the case, no significant water savings would be expected between plots scheduled on the basis of 1 and 3SMW.

The CTV plot required less than half the amount of water required by the WW plot during the entire season. This suggests that using canopy temperature variability as a parameter to initiate

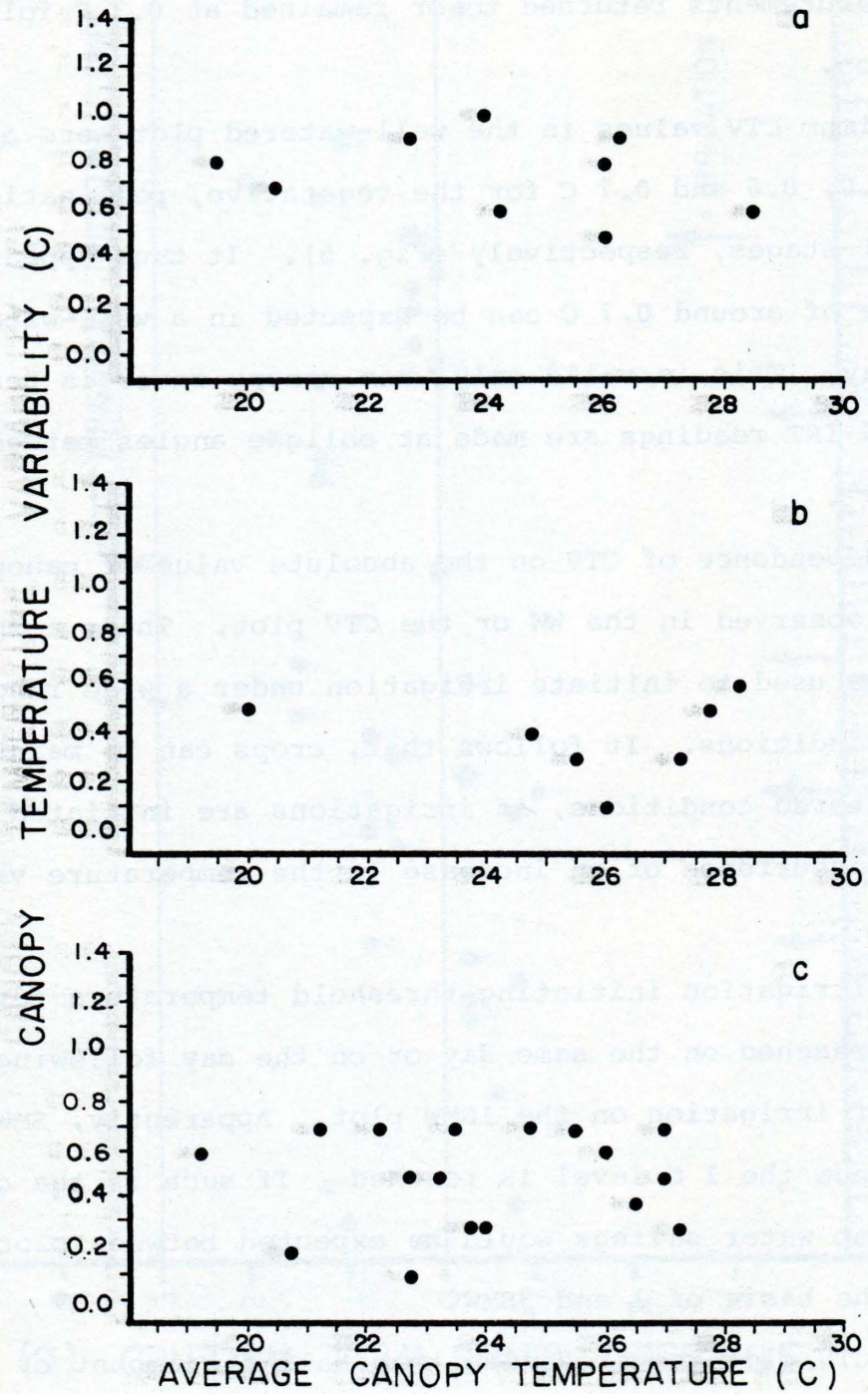


Fig. 5. Canopy temperature variability as a function of average canopy temperature in the well-watered plot for the vegetative (a), pollination (b), and grainfill (c) periods.

irrigation has the potential for significant water savings and for improved efficiency in the use of available soil water.

CTV and the SMW temperature elevations were found to be interrelated (Table 2). No significant relationships existed in any plot during the vegetative stage, probably because of a general lack of stress during this period. The relationship between CTV and SMW in the 1SMW, the 3SMW and the DL plots was significant. The relationship with 1SMW was significant at the 99% level in both the pollination and grainfill stages. The relationship with 3SMW showed significance at the 95% level during the grainfill stage. The relationship with DL showed significance at the 90% level during the grainfill stage. No other correlations were obtained. An example of the relationship between CTV and 1SMW for the grainfill period is shown in Fig. 6.

The regressions indicated that the CTV parameter was more sensitive to water stress than were the SMW parameters. When water stress was mild, SMW was at or very near 0.0 C, while CTV fluctuated between 0.0 and 0.7 C. As water stress increased, both SMW and CTV increased. As the stress became increasingly severe, SMW increased rapidly while CTV began to level off. This accounts for the lower level of significance that was observed for the 3SMW and the DL treatments than was obtained for the 1SMW treatment.

Thus it appears that canopy temperature variability can be used to signal the onset of plant water stress but the severity of plant water stress is probably best indicated by the magnitude of the elevation in average canopy temperature above that of a well-watered reference plot.

Table 2. Summary of regression statistics for comparison of stressed minus well-watered canopy temperature difference (SMW) with canopy temperature variability (CTV) in all growth stages. a, b and c denote significance at 99, 95 and 90 percent, respectively. Average values of CTV and SMW are also listed.

	Irrigation Treatment			
	0.8CTV	1SMW	3SMW	DL
Vegetative				
R^2	0.001	0.035	0.001	0.246
slope	0.03	0.12	0.01	-0.09
y intercept	0.68	0.76	0.26	0.43
avg SMW (C)	-0.3	0.2	0.1	-0.2
avg CTV (C)	0.7	0.8	0.3	0.5
Pollination				
R^2	0.078	0.667a	0.197	0.230
slope	-0.09	0.71	-0.12	0.38
y intercept	0.57	0.68	0.29	0.76
avg SMW (C)	-0.2	0.6	0.5	0.5
avg CTV (C)	0.6	1.1	0.3	0.9
Grainfill				
R^2	0.00	0.440a	0.317b	0.160c
slope	0.00	0.65	0.10	0.24
y intercept	0.48	0.76	0.24	1.01
avg SMW (C)	-0.1	0.2	1.3	1.2
avg CTV (C)	0.5	0.9	0.2	1.2

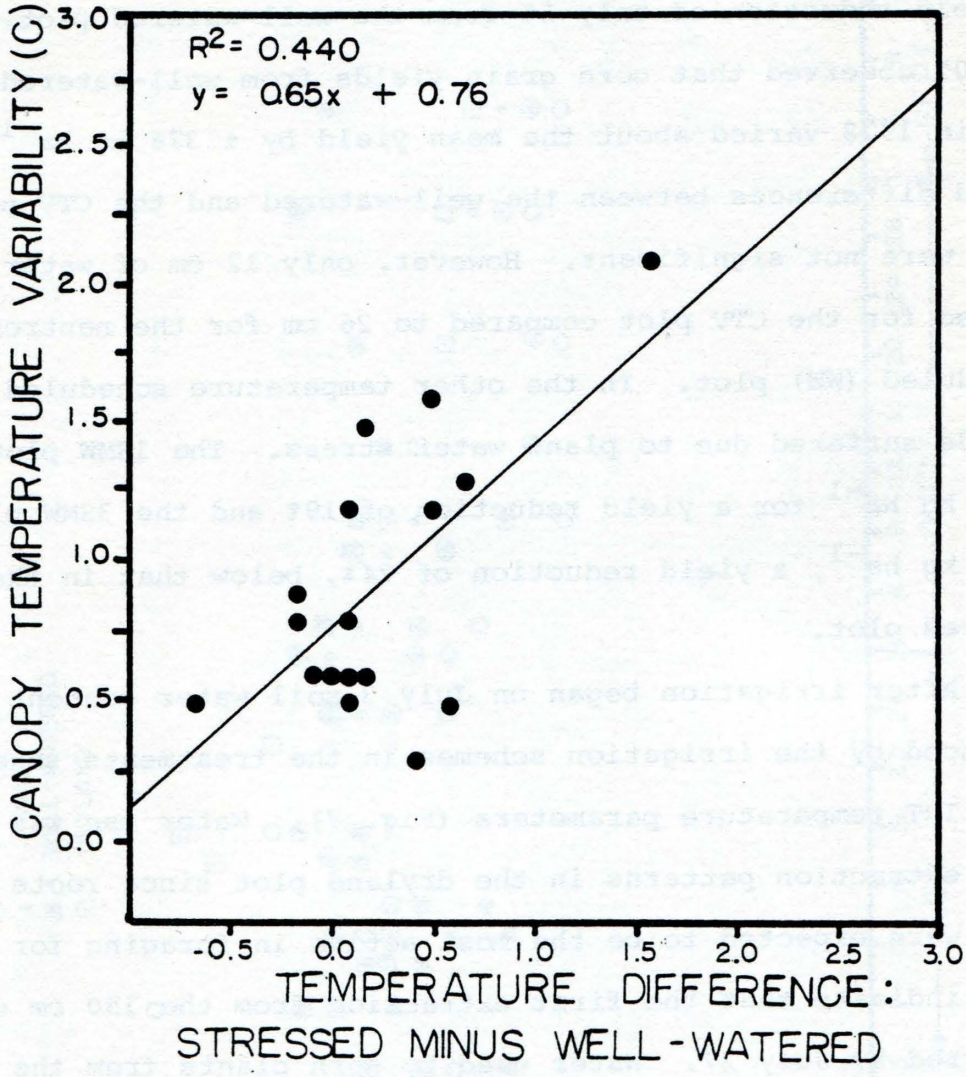


Fig. 6. Comparison of the canopy temperature difference between the SMW plot and the well-watered plot and the canopy temperature variability of the lSMW plot. Data were obtained during the grainfill period.

The maximum grain yield of 7575 kg ha^{-1} was obtained from the well-watered plot. The minimum yield of 4933 kg ha^{-1} was from the dryland plot. This difference represents a yield reduction of 35%. Grain yields from the temperature scheduled plots fell between these extremes. The CTV plot yielded 7202 kg ha^{-1}. This is a yield reduction of only 5% from the well-watered plot. Gardner (1980) observed that corn grain yields from well-watered plots at SAL in 1978 varied about the mean yield by ± 376 kg ha^{-1}. Thus yield differences between the well-watered and the CTV plot in 1979 were not significant. However, only 12 cm of water was required for the CTV plot compared to 26 cm for the neutron probe scheduled (WW) plot. In the other temperature scheduled plots, yields suffered due to plant water stress. The 1SMW plot yielded 6197 kg ha^{-1} for a yield reduction of 19% and the 3SMW plot yielded 5815 kg ha^{-1}, a yield reduction of 24%, below that in the well-watered plot.

After irrigation began on July 3 soil water content was influenced by the irrigation schemes in the treatments scheduled with IRT temperature parameters (Fig. 7). Water use was compared with extraction patterns in the dryland plot since roots in that plot were expected to be the most active in foraging for water. Data indicate that the first extraction from the 150 cm depth occurred by July 27. Water used by corn plants from the 150 cm level in the DL plot was small--only 2 cm for the entire season.

Differences in the soil water content due to irrigation treatment did not appear until after the beginning of the pollination period. The general pattern that emerged after July 23 was one in which the average volumetric water content was highest

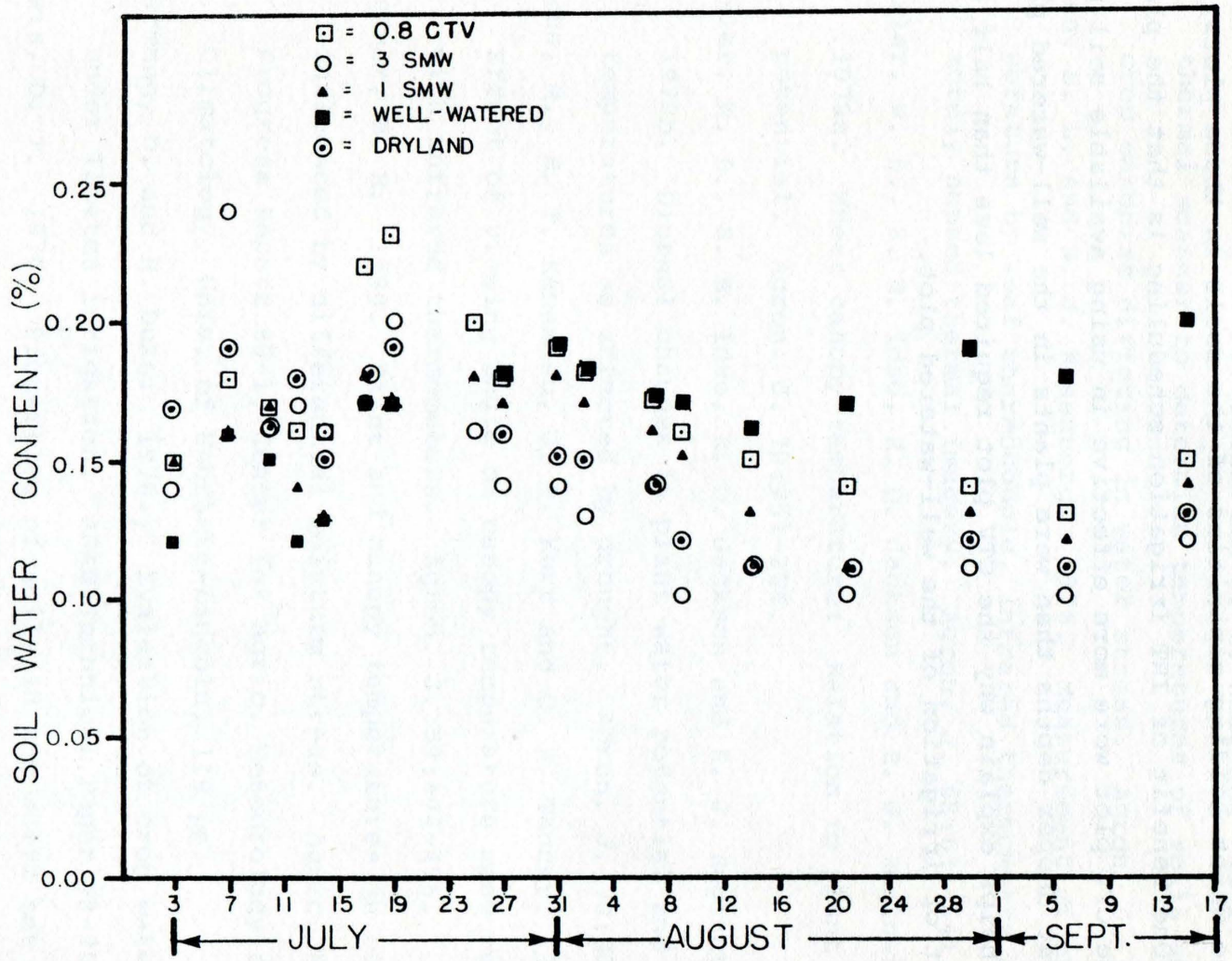


Fig. 7. Pattern of soil water content (% by volume) for the depths of active water extraction in each plot. Root depths ranged from 0-60 cm on July 3 to 0-150 cm on July 25 and for the duration of the study.

in the WW plot, followed in order by the 0.8 CTV, the 1SMW, the DL and the 3SMW plots. The reason that the 3SMW plot showed a small but consistent pattern of a lower water content than did did the dryland plot is unknown but probably reflects differences in the water holding capacities of the soils in these plots.

One benefit of IRT irrigation scheduling is that the plants in the CTV plot were more effective in using available soil moisture at deeper depths than were plants in the well-watered plot. This helps explain why the CTV plot required less than half the amount of irrigation of the well-watered plot.

REFERENCES

Aston, A. R. and C. H. M. van Bavel. 1972. Soil surface water depletion and leaf temperature. Agron. J. 64:368-373.

Bartholic, J. F., L. N. Namken and C. L. Wiegand. 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. Agron. J. 64:603-608.

Blad, B. L. and N. J. Rosenberg. 1976. Measurement of crop temperature by leaf thermocouple, infrared thermometry and remotely sensed thermal imagery. Agron. J. 68:635-641.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978a. Wheat canopy temperature: Relation to plant water potential. Agron. J. 70:251-256.

Ehrler, W. L., S. B. Idso, R. D. Jackson and R. J. Reginato. 1978b. Diurnal changes in plant water potential and canopy temperatures as affected by drought. Agron. J. 70:998-1004.

Fuchs, M., E. T. Kanemasu, J. P. Kerr and C. B. Tanner. 1967. Effect of viewing angle on canopy temperature measurements with infrared thermometers. Agron. J. 59:494-496.

Gardner, B. R. 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. Agric. Meteorol. Progress Report 80-1, Center for Agric. Meteorology and Climatology, Univ. of Nebraska-Lincoln, 119 pp.

Heermann, D. and H. Duke. 1978., Evaluation of crop water stress under limited irrigation. ASAE Technical Paper 78-2556.

Lewis, D. T. 1976. Properties of soils in the solid set irrigation area of the Sandhills Agricultural Laboratory, Univ. of Nebraska Agric. Expt. Sta. Research Bull. #278, 14 pp.

Millar, A. A., R. E. Jensen, A. Bauer and E. B. Norum. 1971. Influence of atmospheric and soil environmental parameters on the diurnal fluctuations of leaf water status of barley. Agric. Meteorol. 8:93-105.

Millard, J. P., R. D. Jackson, R. C. Goettelman, R. J. Reginato and S. B. Idso. 1978. Crop water-stress assessment using an airborne thermal scanner. Photogrammetric Engr. and Remote Sensing 44:77-85.

Nixon, P. R., L. N. Namken and C. L. Wiegand. 1973. Spatial and temporal variations of crop canopy temperatures and implications for irrigation scheduling. Proc. Conf. on Earth Resources Observation and Information Analysis System: Remote Sensing of Earth Resources. Vol II, F. Shahrokhi (ed.) Tullahoma, Tennessee, pp. 643-657.

Tanner, C. B. 1963. Plant temperatures. Agron. J. 55:210-211.

Wiegand, C. L. and L. N. Namken. 1966. Influences of plant moisture stress, solar radiation and air temperatures on cotton leaf temperature. Agron. J. 58:582-586.

CHAPTER VIII

CANOPY TEMPERATURE OF SEVERAL CORN HYBRIDS IN RESPONSE TO WATER STRESS AND PLANT POPULATION

B. R. Gardner, B. L. Blad, R. E. Maurer
D. G. Watts, G. D. Wilson and K. L. Clawson

ABSTRACT

Canopy temperature (T_{IR}) was measured with an infrared thermometer on nine different hybrids of corn (Zea mays L.) during 1978 and 1979. Three irrigation treatments were used to develop water stress across a plot at different stages of growth. In 1979 plots were planted at four plant population levels and subjected to several irrigation regimes.

The objectives of this study were 1) to relate grain yields of the various hybrids to crop temperatures that develop in response to water stress and 2) to determine how plant population interacts with water stress to determine canopy temperature.

The yield in all of the nine hybrids was reduced to about the same degree below that in fully irrigated corn. Estimation of yield reductions due to water stress requires knowledge of the maximum yield potential of the hybrid under fully irrigated conditions and of the degree of crop stress, which can be calculated in terms of TSD values (TSD is defined as the mid-day canopy temperature difference between well-watered and stressed plants). Our results suggest that a temperature stress day of 1 C predicts a yield reduction of about 0.7%.

Under fully irrigated conditions values of T_{IR} were not influenced by plant population. Under water stress conditions, T_{IR} values were consistently 1-2 C higher with high plant populations

than with low plant population. This higher canopy temperature is attributed to greater competition in areas of higher population leading to more rapid depletion of available water.

INTRODUCTION

Gardner et al. (Chapter VI) reported a similar relationship between crop temperature and the percent grain-yield reductions caused by water stress in two sorghum hybrids. This finding is encouraging to those who wish to estimate grain yield potential with remote sensing techniques. The purposes of the study reported here were 1) to study the response of grain yield in nine hybrids of corn (Zea mays L.) to crop temperature regimes caused by a range of water stress conditions and 2) to determine the extent to which plant population interacts with water stress to affect crop canopy temperature.

MATERIALS AND METHODS

This study was conducted during 1978 and 1979 at the University of Nebraska Sandhills Laboratory, near Tryon, Nebraska (41° 37' N; 100° 50' W; 975 m above mean sea level). Details of the irrigation system which was used in the study to evaluate the response of the nine corn hybrids to water stress are given in Chapter II. In 1978, three hybrids of corn: Dekalb XL-15A, Pioneer 3148 and Prairie Valley 215 were planted in plots measuring 9 m (N to S) and 19 m (E to W) (Fig. 1). Two irrigation treatments were used: I-G-I and G-G-I where I stands for full irrigation and G stands for a gradient irrigation of a plot during either the vegetative, pollination or grain-fill periods. In the G treatment, the side of the plot near the irrigation line

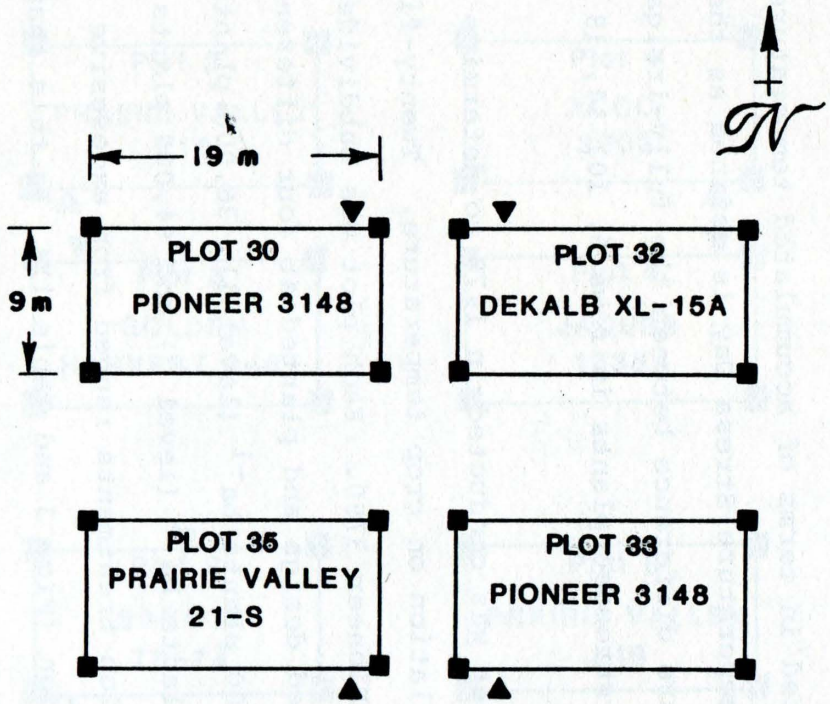


Fig. 1. Map of the plots used in the 1978 corn hybrid study. Locations of the solid-set sprinklers are represented by squares. The triangles show locations of the fully irrigated row when an irrigation gradient was applied.

receives full irrigation and the other side receives no irrigation. The nine plots of Pioneer 3780 described in Chapter II were also included in this study. In 1979, five corn hybrids: Jacques 1033A, Prairie Valley 21 S, Sokota TS 74, Acco 3002 and Golden Harvest 2457 were planted in 9 m (N to S) by 19 m (E to W) plots (Fig. 2). All plots were irrigated with a G-I-G treatment. The percent reduction in yields of each of these hybrids due to water stress was evaluated in terms of accumulated temperature stress days (TSD). A Temperature Stress Day is defined as the mid-day canopy temperature difference between the fully-irrigated plants in row 2 and the stressed plants in rows 6, 10, 14, 18 or 22.

A separate experiment was conducted in 1979 to determine the effect of plant population on crop temperature. Twenty-five plots were planted with Pioneer 3780. Each plot was subdivided in a completely randomized design and planted at four different population levels: 26,000 plants ha^{-1} (level 1), 36,000 plants ha^{-1} (level 2), 54,000 plants ha^{-1} (level 3) and 64,000 plants ha^{-1} (level 4). Irrigation treatments ranged from excesssive irrigation to no irrigation (Fig. 3 and Table 1). In this chapter, we report only the data collected in plots 23, 27, 29 and 32 (Fig. 3).

Infrared thermometer (IRT) measurements were made with a Barnes PRT-5[1] in 1978 and a Telatemp model Ag 42[2] in 1979. In both years measurements began at the beginning of the pollination

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[1]Barnes Engineering Co., 30 Commerce Rd., Stamford, CT.

[2]Telatemp Corp., P.O. Box 5160, Fullerton, CA.

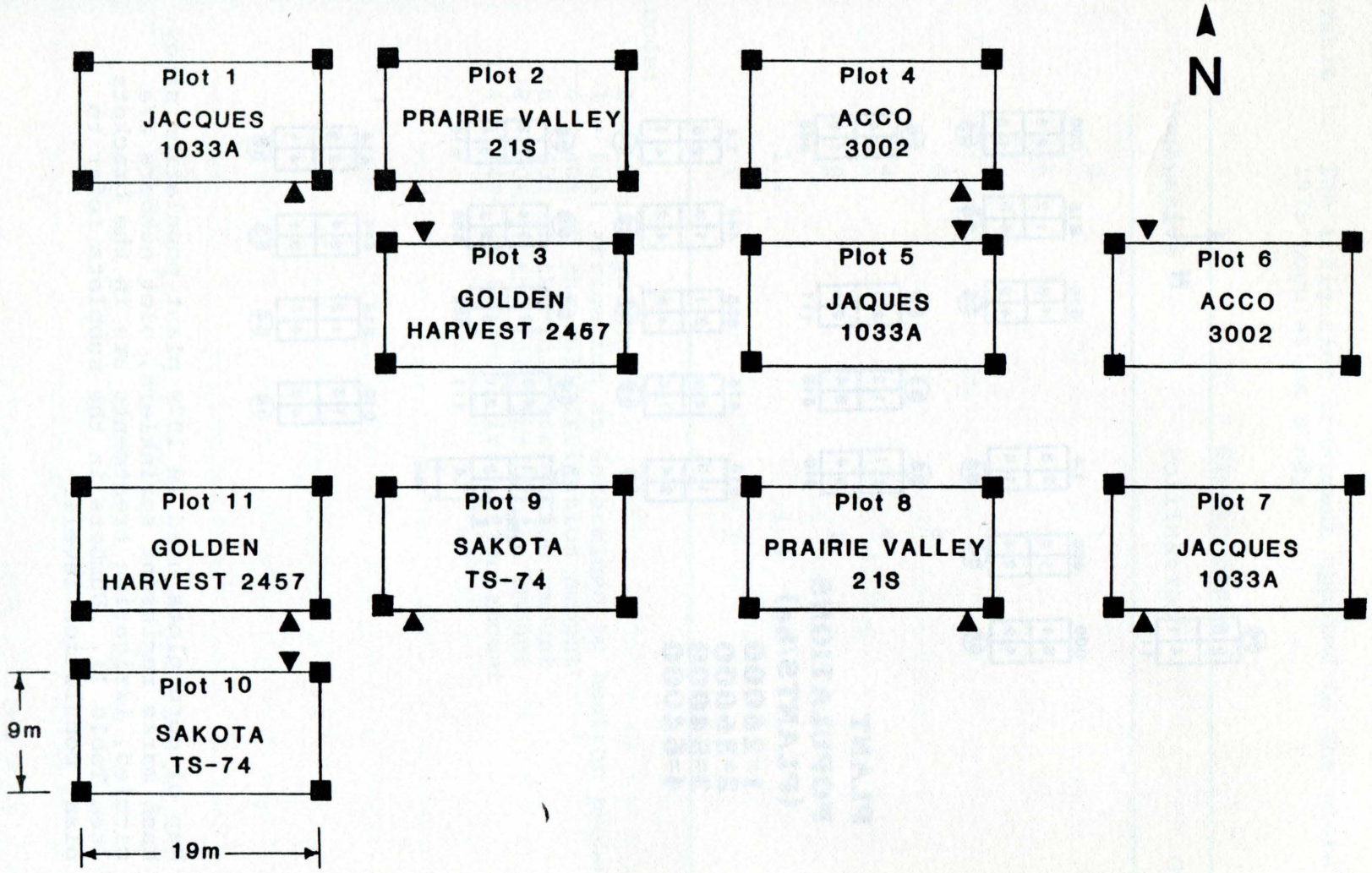


Fig. 2. Map of eleven plots used in the 1979 corn hybrid study. Symbols are the same as in Fig. 1.

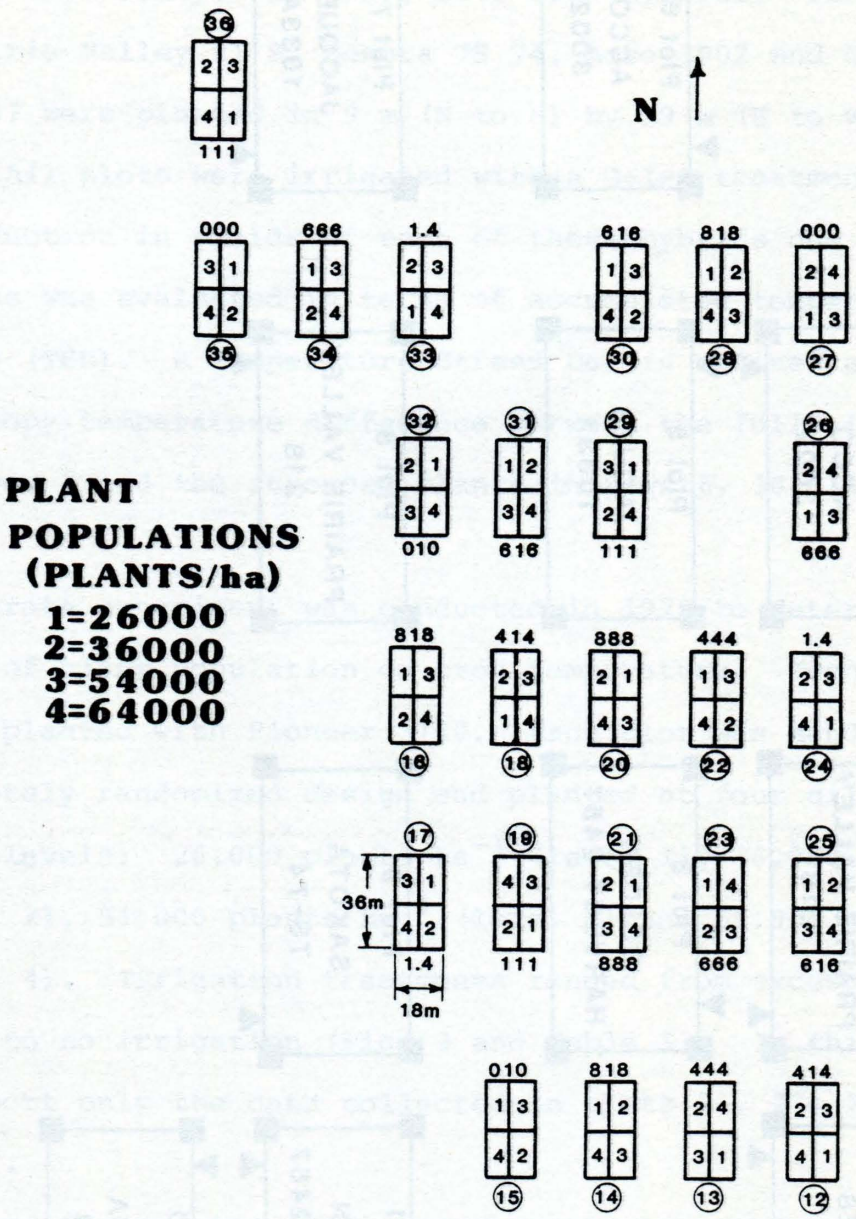


Fig. 3. Map of corn plots used in 1979 plant population study. Hash marks represent sprinklers, plot numbers are circled, irrigation treatments are in the brackets (see Table 1). Numbers in the subplots refer to plant population levels.

Table 1. The irrigation treatment applied to the plots in the 1979 population study.

Growth Stage		
Vegetative	Pollination	Grain Fill
0	1	0
6	1	6
6	6	6
8	8	8
4	4	4
8	1	8
1.4	1.4	1.4
1	1	1

Code:
0 = no irrigation
1 = full irrigation as determined by neutron probe sampling
4 = 40% of the full irrigation amount
6 = 60% of the full irrigation amount
8 = 80% of the full irrigation amount
1.4 = 140% of the full irrigation amount

stage in all varieties. IRT measurements were made between 1300 and 1500 hrs on almost every day throughout the remainder of the season.

A hailstorm, with stones up to 3 cm in diameter, struck the experimental site on July 16. Many of the emerged leaves, were shredded but stalk damage was minimal. This damage altered the plant canopy and may have permitted the IRT to view deeper into the plant canopy, especially with gusty winds. The temperature variability due to wind gusts alone was, subsequently, estimated to be approximately 0.5 C (Chapter IX). Since the effect of wind gusts should be random in nature, we interpreted measured temperature differences of 1 C or more to be real.

RESULTS AND DISCUSSION

Hybrid Study

Only small grain yield reductions occurred in the various corn hybrids in response to increased canopy temperature caused by water stress. The percent yield reduction (Fig. 4) is about the same for all hybrids at a given value of ΣTSD. Most yield values are within ±5% of the curve fitted in the figure by polynomial regression. Virtually all values are within ±10%. The quadratic term of the equation appeared to have little effect except at large values of ΣTSD so that a linear regression was deemed adequate to describe the relationship. This resulted in a slight reduction in R^2 from 0.91 to 0.87. We calculated that, based upon slope of the linear regression line, about 0.7% of the maximum yield potential (yield achieved with no water stress) is lost for each unit of ΣTSD experienced by the corn.

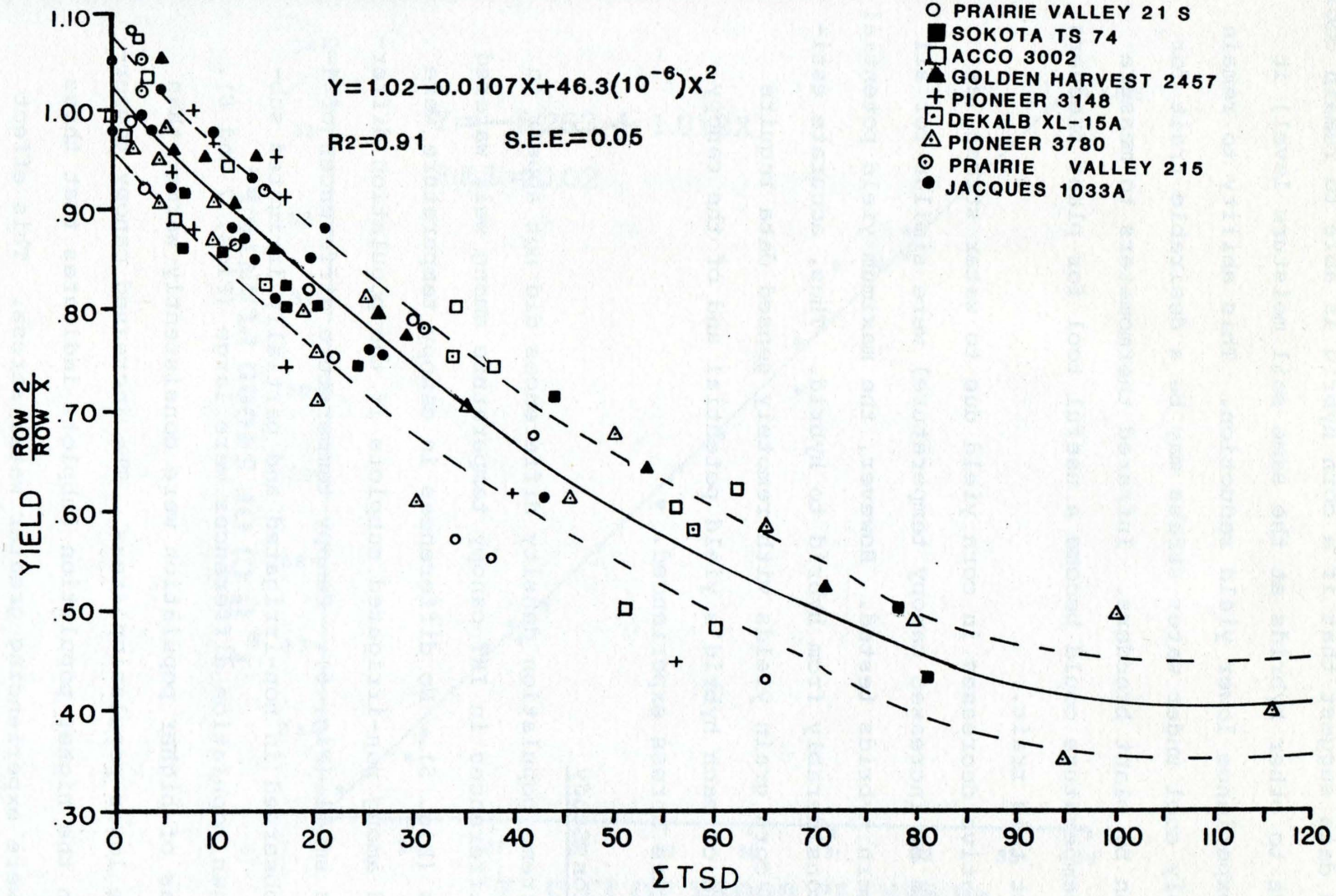


Fig. 4. Comparison of grain yields, as a fraction of the row 2 (fully irrigated) yields, for nine corn hybrids as a function of ΣTSD values. Crop temperature data used to obtain ΣTSD values were obtained during the pollination and grain-fill periods. Dashed lines indicate the standard error of estimate.

The data suggest that if a corn hybrid is able to remain cool (relative to other hybrids at the same soil moisture level) it should experience lower yield reduction. This ability to remain relatively cool under water stress may be a desirable trait for selection by plant breeders. Infrared thermometers to measure canopy temperature could become a useful tool for plant breeders to detect this trait.

Relative decreases in corn yield due to water stress (as indicated by increased canopy temperature) were similar for all of the corn hybrids tested. However, the maximum yield potential varies considerably from hybrid to hybrid. Thus, accurate estimates of corn grain yields with remotely sensed data require knowledge of each hybrid's yield potential and of the canopy temperature stress experienced.

Population Study

Extreme population density differences did not appear to cause differences in IRT canopy temperature among well watered subplots (Fig. 5). No differences in canopy temperature were observed among non-irrigated subplots if the population difference was small (Fig. 6). Canopy temperature differences of 1-2 C were observed in non-irrigated and partially irrigated subplots when population differences were large (Figs. 7 and 8). The areas of higher population were consistently warmer than were the lower population areas. The increased canopy temperature in the higher population subplots indicates that these plants were experiencing greater water stress. This effect is expected since competetion for water is greater in higher

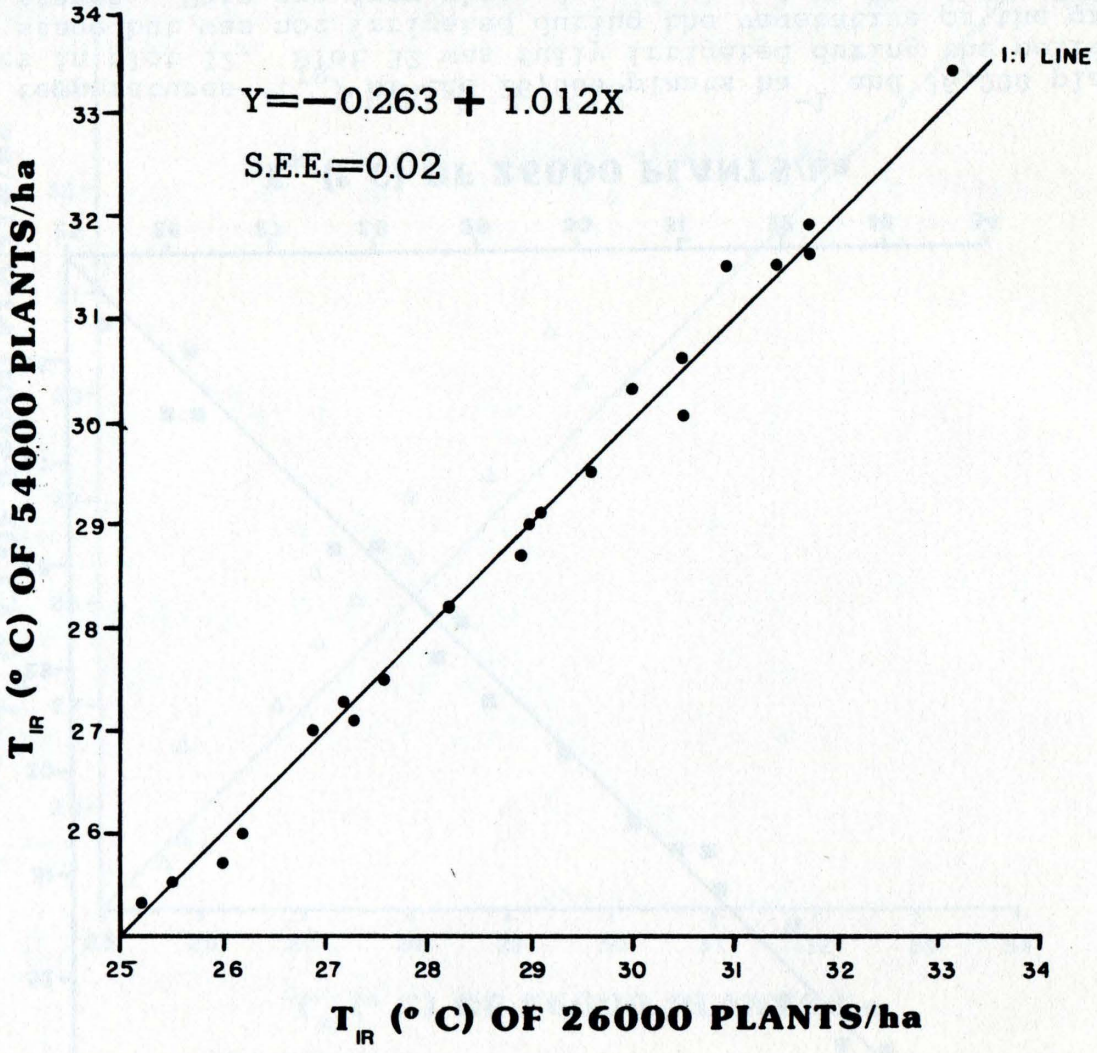


Fig. 5. Canopy temperatures (T_{IR}) of the 26,000 plants ha^{-1} and 54,000 plants ha^{-1} subplots in plot 29 which was fully irrigated. Data are from clear days during July 25 to September 5, 1979.

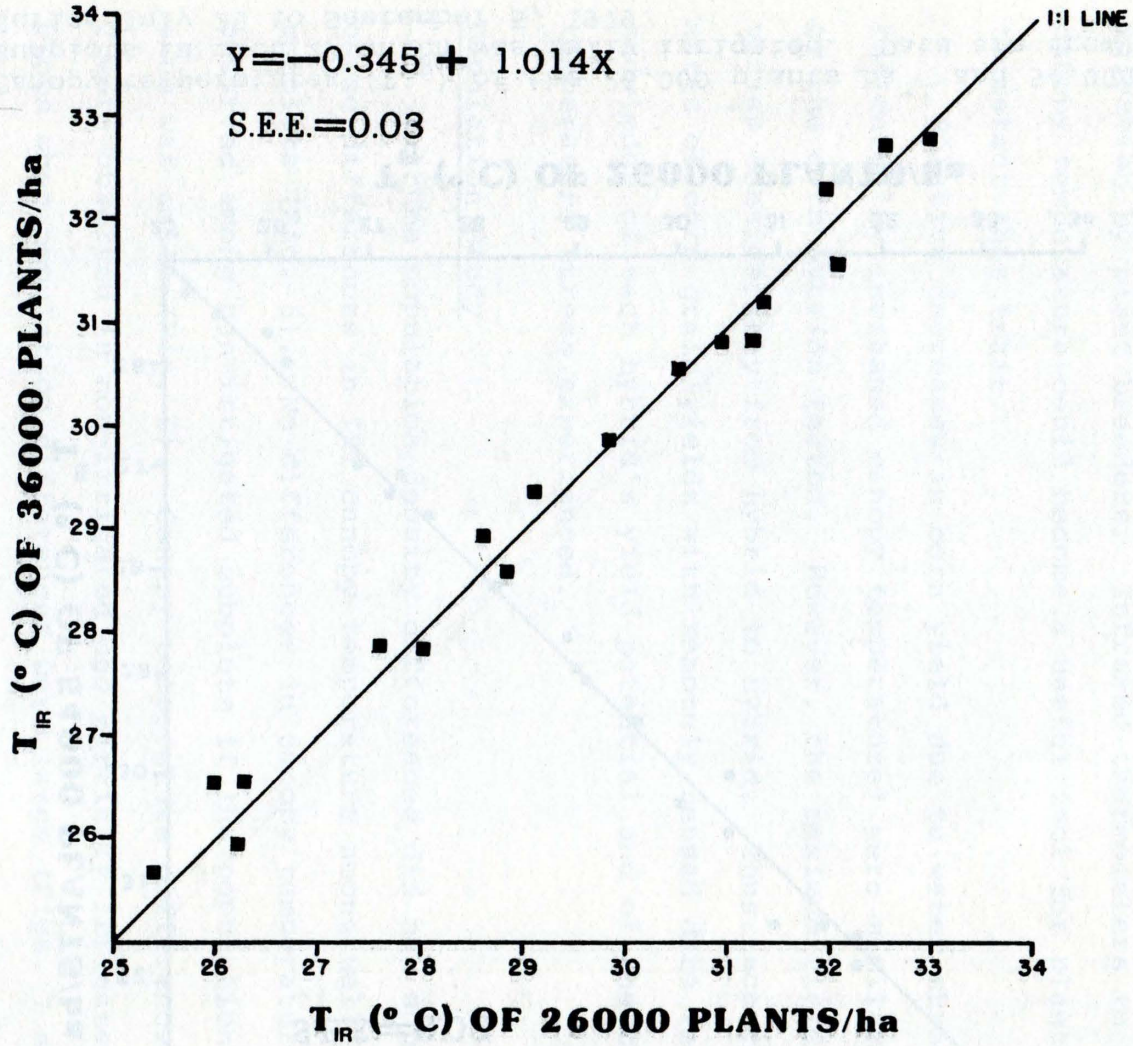


Fig. 6. Canopy temperatures (T_{IR}) of the 26,000 plants ha^{-1} and 36,000 plants ha^{-1} subplots in plot 32. Plot 32 was fully irrigated during the pollination growth stage but was not irrigated during the vegetative or the grain-fill growth stages. Data are from clear days during July 25 to September 5, 1979.

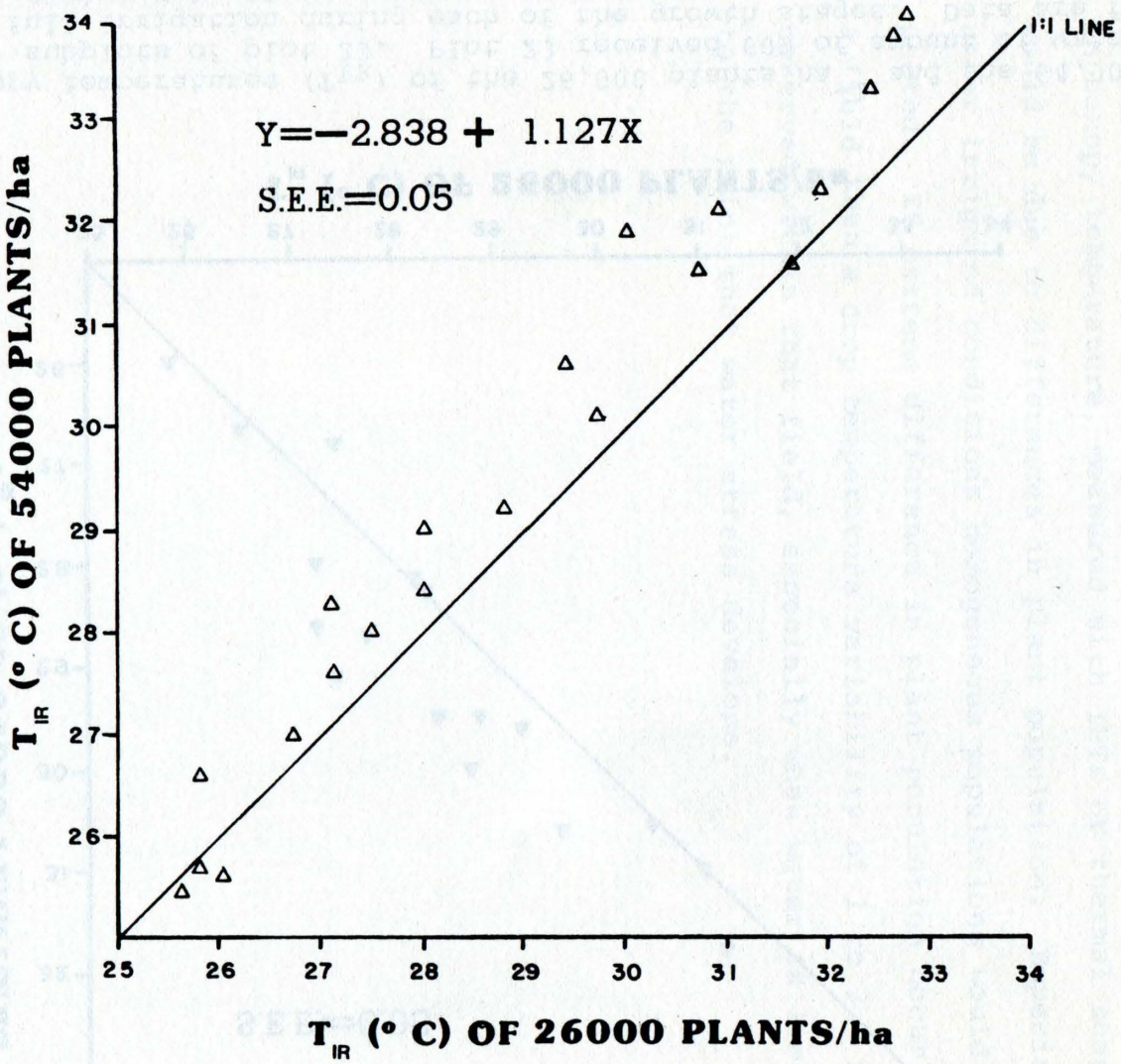


Fig. 7. Canopy temperatures of the 26,000 plants ha^{-1} and the 54,000 plants ha^{-1} subplots in plot 27. Plot 27 received no irrigation during the growing season. Data are from clear days during July 25 to September 5, 1979.

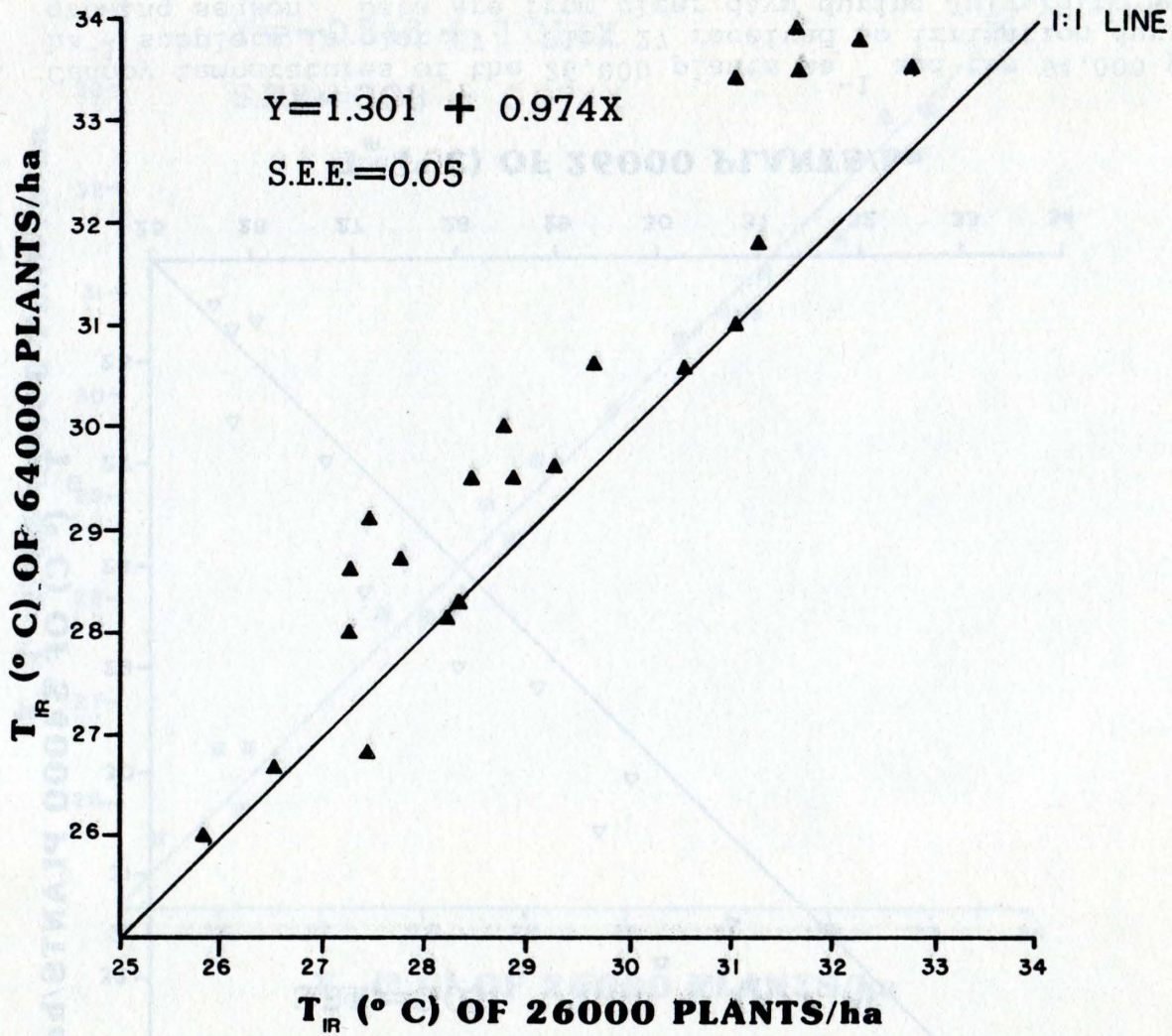
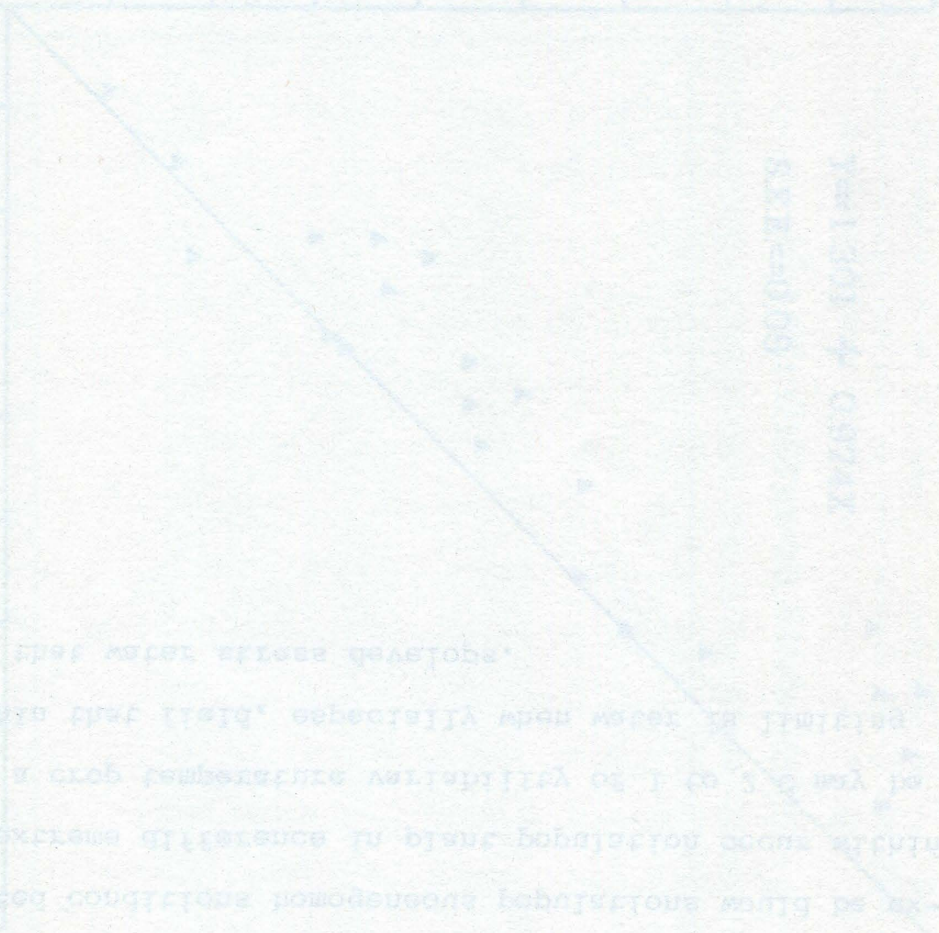


Fig. 8. Canopy temperatures (T_{IR}) of the 26,000 plants ha^{-1} and the 64,000 plants ha^{-1} subplots of plot 23. Plot 23 received 60% of amount of water required for full irrigation during each of the growth stages. Data are from clear days during July 25 to September 5, 1979.

population. This effect leads to more rapid consumption of any available soil moisture which, in turn, causes more pronounced water stress resulting in warmer plants.

In commercial fields of corn it is unlikely that variations in canopy temperature, measured with IRTs or thermal scanners would be due to differences in plant population. Especially under irrigated conditions homogeneous populations would be expected. If extreme difference in plant population occur within a field then a crop temperature variability of 1 to 2 C may be observed within that field, especially when water is limiting to the point that water stress develops.



CHAPTER IX

EFFECTS OF CLOUDS, WIND, SOIL, NITROGEN CONTENT, SUN POSITION AND VIEWING DIRECTIONS ON CORN CANOPY TEMPERATURES

K. L. Clawson, B. L. Blad and B. R. Gardner

ABSTRACT

Canopy temperatures measured with infrared thermometers (IRT's) are useful for evaluating crop water stress. To properly evaluate IRT data, however, the effects of various environmental factors should be understood. This experiment done to study the effects of cloud cover, windspeed, level of soil nitrogen, position of the sun in the sky and IRT viewing direction on canopy temperature measurements made in corn (Zea mays L.) with an IRT.

Because canopy temperatures are affected by environmental factors as well as by plant water stress, several cause and effect relationships were identified. Variations in wind speed were found to have an effect on canopy temperatures. Wind gusts cooled the canopy by about 0.5 C. Canopy temperatures rose by about 1 C during calm periods. Decreases in solar radiation at midday due to clouds caused an immediate drop in canopy temperature of about 2.5 C. After the cloud moved to unblock the sun, the canopy returned to the same temperature as before the cloud blockage within about one minute.

When soil nitrogen was severely limiting an increase in canopy temperature of about 1 C was found as was found as compared to that of plants grown under non-limiting soil nitrogen conditions. That temperature increase did not occur under moderately nitrogen limiting conditions suggests that water stress detection with

crop temperature data will not be masked at the soil nitrogen concentrations found under normal field conditions. It further suggests that infrared thermometry can be used to detect nitrogen stress only under severely nitrogen limited conditions.

Under well-watered conditions, only very small canopy temperature differences were observed when the instrument was aimed north or south. When soil water became limiting, however, the temperature of the corn with a southern exposure (observer facing north) was 1 to 2 C warmer than that of the plants with a northern exposure.

In north-south oriented rows, canopy temperatures measured on the east side of the row were as much as 0.8 C warmer than those measured on the west side of the row until about 1000 hrs solar time. This was attributed to differential heating of the canopy caused by the position of the sun at relatively low angles in the eastern part of the sky.

INTRODUCTION

Canopy temperatures have been used by researchers to evaluate plant water stress (Gardner, 1980; Ehrler et al., 1978a, b) and to schedule irrigation (Clawson, 1980 and Chapter VII). Canopy temperature is dependent, not only on plant water stress, but also on various environmental factors. A number of models have been developed to explain leaf temperature dependence on energy exchange (e.g. Gates, 1964; Linacre, 1964; Wolpert, 1962; Edling et al., 1971; Norman, 1979). These models are based on energy balance considerations that involve conservation of mass and energy. These processes depend on physical and physiological

functions, where heat is gained by the plant from solar radiation and lost by convection, radiation and evaporation. Theory thus predicts a dependence of leaf temperature on radiation, wind speed and transpiration. Under constant meteorological conditions, stomatal closure in response to water stress will cause the leaf temperature to rise because of reduced transpirational cooling (Hsaio, 1973). The ways in which plant canopy temperature responds to different environmental conditions must be known before canopy temperature data can be properly interpreted.

Plant temperature responds to variations in cloud cover. Early reseachers detected as much as 7 C difference between shaded and unshaded plants (Clum, 1926). Miller and Saunders (1923) found that leaf temperature differences between turgid and wilted leaves were not as great under heavy cloud cover as they were in full sunlight. Temperature differences as great as 8 C for tomato (Lycopersicon esculentum) leaves under sunny and cloudy conditions were reported by Waggoner and Shaw (1952). Stone et al. (1975) reported sorghum (Sorghum bicolor L. Moench) canopy temperature fluctuations of 3 C during a three minute time span as incoming shortwave radiation fluctuated between 350 and 1000 Wm^{-2}. Gardner (1980) found that cloud passage over stressed and non-stressed corn (Zea mays L.) caused canopy temperatures to decrease by 5.2 and 3.6 C, respectively.

Changes in wind speed can also cause leaf temperature fluctuations. Curtis (1936) found leaf temperature changes of 5 C in response to varying wind speeds. Ansari and Loomis (1959) investigated the cooling effect of wind on pepper (Piper nigrum) leaves in full sunlight. They found that a 2.2 m sec^{-1} wind

cooled leaves by about half as much as did shading the leaves.

In addition to radiative flux density variations, the position of the sun in the sky as well as row orientation can affect the temperature of crop canopies measured with infrared thermometers (IRT). Gates and Tantraporn (1952) showed that in the IR wave-lengths, reflectivity is slightly specular. However, this effect is probably of little consequence to infrared thermometry due to the low ratio of reflected to emitted radiation in the thermal IR wavelengths. Fuchs et al. (1967) found that IRT measured canopy temperatures of alfalfa were unaffected by either solar elevation or azimuth. The viewing angle employed with the IRT also appeared to have little effect except at extremely large or small angles. At intermediate viewing angles, canopy temperatures fluctuated by no more than about 0.3 C. Soybean canopy temperatures, on the other hand, were affected by row orientation, azimuthal and elevation angle. This effect was attributed to uneven heating of the soybean row.

Reports of experiments detailing the dependence of canopy temperature on nutrient stress are not found in the literature. The study reported here was designed to 1) determine the magnitude of canopy temperature fluctuations caused by wind and cloud cover, 2) determine whether canopy temperature is affected by a shortage of available nitrogen and 3) ascertain the dependence of canopy temperature on the sun's position in the sky and on the direction that the IRT is aimed.

METHODS AND MATERIALS

This study was conducted in the solid set irrigation area (Fig. 1) at the Sandhills Agricultural Laboratory (41° 37' N,

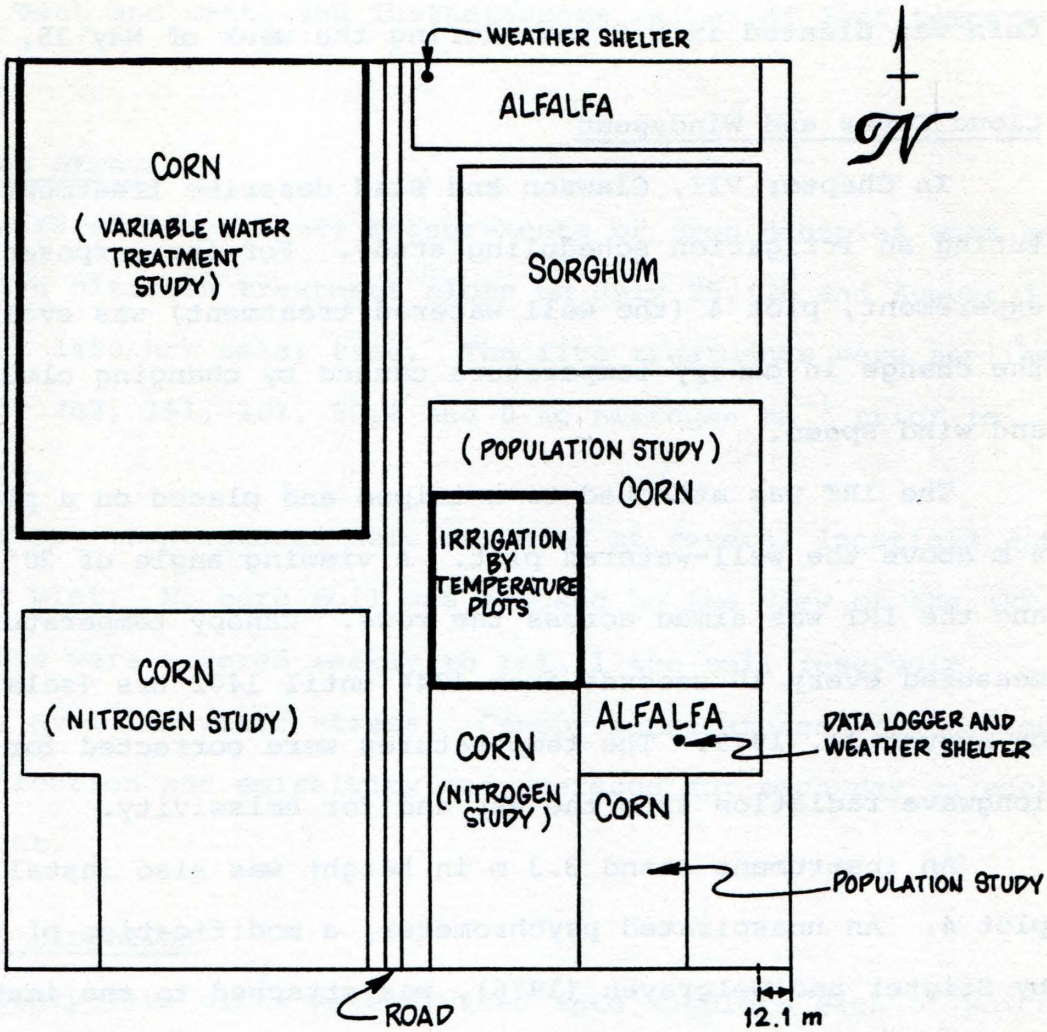


Fig. 1. Experimental plots at the Sandhills Agricultural Laboratory. The plots used in this study are outlined by the dark borders.

100° 50' W, 975 m above m.s.l.). Plot size was 28.3 m E-W by 56.6 m N-S. Each plot was irrigated with sprinklers about 2 m above the ground and spaced 18.9 m apart N-S by 29.3 m E-W. Corn was planted in N-S rows during the week of May 15, 1979.

Cloud Cover and Windspeed

In Chapter VII, Clawson and Blad describe treatments constituting an irrigation scheduling study. For the purposes of this experiment, plot 4 (the well watered treatment) was evaluated for the change in canopy temperature caused by changing cloud cover and wind speed.

The IRT was attached to a tripod and placed on a platform 4 m above the well-watered plot. A viewing angle of 30° was used and the IRT was aimed across the rows. Canopy temperatures were measured every 10 seconds from 1344 until 1402 hrs (solar time) on August 11, 1979. The temperatures were corrected for reflected longwave radiation from the sky and for emissivity.

An instrument stand 3.3 m in height was also installed in plot 4. An unaspirated psychrometer, a modification of the design by Stigter and Welgraven (1976), was attached to the instrument stand at the top of the canopy. Crop height was approximately 2.3 m. Evanohm-constantan thermocouples were attached to the abaxial leaf surface of fully sunlit leaves at the top of canopy near the psychrometer. Five thermocouples were wired in parallel to insure spatial averaging of leaf temperature.

Wind speed and direction were monitored at a weather station at a height of 2 m in the nearby alfalfa plots (Fig. 1). Data were recorded on the hour (solar time) with a Campbell Scientific

digital recorder.[1] Input modules provided continuous hourly averages of temperatures from the mini-psychrometer, mean wind run and wind speeds of four integrated vector components (north, south, east and west) and instantaneous values of leaf temperatures.

Nitrogen Stress

Infrared temperature measurements of crop canopies were made over five nitrogen treatment plots on July 25, 26 and August 1 at about 1400 hrs solar time. The five treatments were applications of 202, 151, 101, 50.4 and 0 kg nitrogen ha^{-1} prior to planting.

Canopy temperatures were measured at several locations within each plot. No bare soil was exposed to the view of the IRT. All plots were watered weekly to refill the soil reservoir, thereby avoiding water stress. Canopy temperatures were corrected for reflection and emissivity and averaged for each day on each treatment.

Viewing Direction

Twenty-five plots were divided into subplots each of which had a different population density. Population densities ranged from sparse (26,000 plants ha^{-1}) to dense (64,250 plants ha^{-1}). 54,500 plants ha^{-1} is considered an optimum population for this region of Nebraska. Irrigation levels ranging from none (dryland) to over-irrigation (140% of that required to restore the soil to field capacity) were randomly assigned to each of the twenty-five

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[1]Campbell Scientific, Inc., Logan, Utah (Model CR5).

plots (Fig. 2). Details of the plot arrangement and water treatment are given in Chapter VIII.

IRT measurements were made over each plot between 1200 and 1400 hours solar time from July 25 to August 31. Two spot measurement of canopy temperature were made in two of the four population subplots in every plot. The plot number, plot treatment and direction of view of the plots used to delineate the effects of north vs south viewing direction are summarized in Table 1. The reader should keep in mind that when the observer faces north, he is viewing the side of the canopy facing the sun at mid-day.

Canopy temperature measurements were paired according to population density, irrigation treatment and direction of IRT view. Mean square error (mse) was calculated for each of these ten matched temperature measurements. Standard deviation ($\hat{\sigma}$) of each temperature mean was then estimated by:

$$\hat{\sigma} = \sum_{j=1}^{11} \text{mse}/13$$

Canopy temperatures of identical irrigation and population density treatments were then compared with those for the opposing view directions. A test statistic (t) was computed for each of the seven pairs by:

$$t = |\bar{x}_n - \bar{x}_s|/\hat{\sigma}$$

where $\bar{x}_n$ and $\bar{x}_s$ are the canopy temperatures averaged over the period of measurement for plots having identical water and population treatment with north (subscript n) and south (subscript s) view directions, respectively.

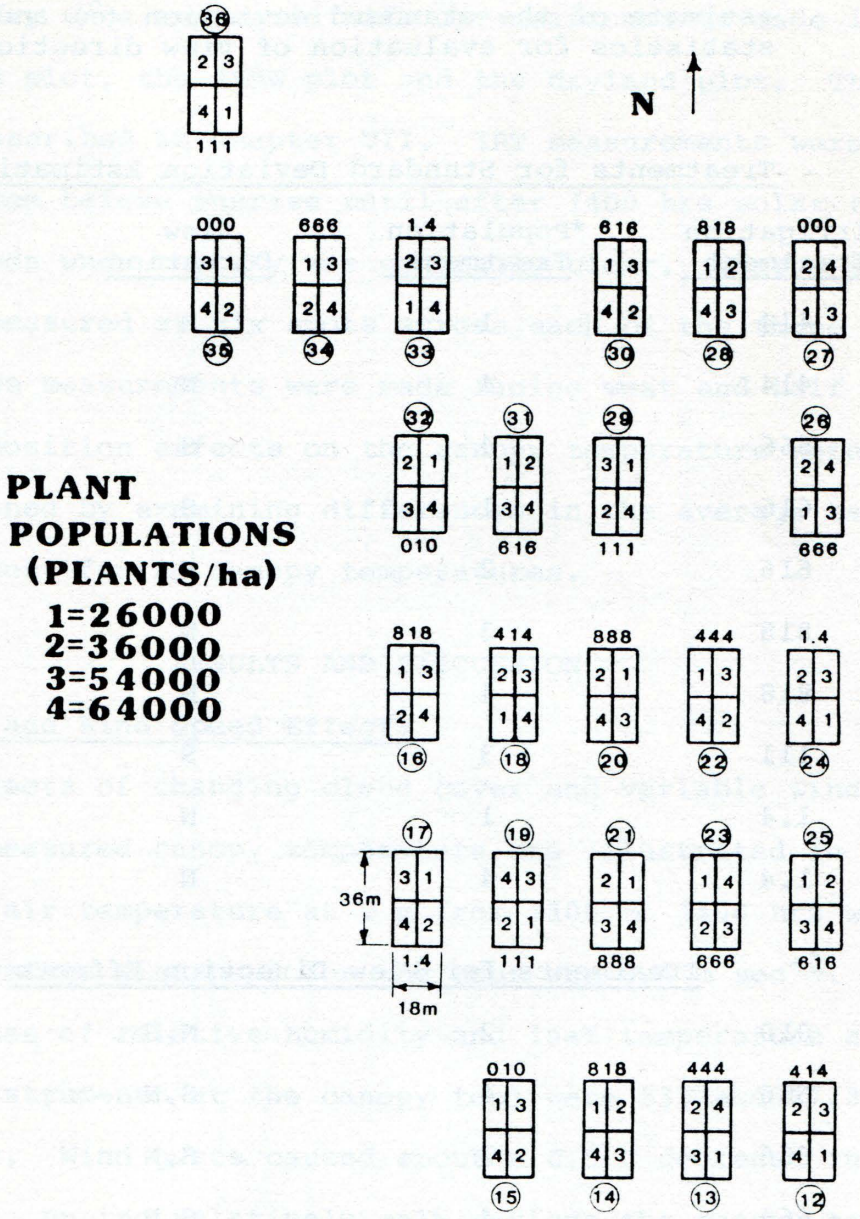


Fig. 2. Map of corn plots used in 1979 viewing direction experiment. Plot numbers are circled, irrigation treatments are in brackets, and numbers in subplots represent plant population levels.

Table 1. Summary of the replicated treatments used to obtain the estimate of the standard deviation ($\hat{\sigma}$) and the test statistics for evaluation of view direction effects.

Treatments for Standard Deviation Estimation

*Irrigation Treatment	*Population Treatment	View Direction	Plot Number
414	1	N	12,18
414	4	N	12,18
666	4	S	23,26
616	1	S	25,31
616	2	S	25,31
818	3	N	14,28
818	4	N	14,16,28
111	3	S	19,29,36
1.4	1	N	24,33
1.4	4	N	24,33

Treatments for View Direction Effects

010	2	N,S	15,32
666	4	S,N	23,34
666	2	S,N	26,34
666	4	S,N	26,34
616	2	S,N	25,30
1.4	1	S,N	17,24
1.4	1	S,N	17,33

*For explanation of these treatments, see Chapter VIII.

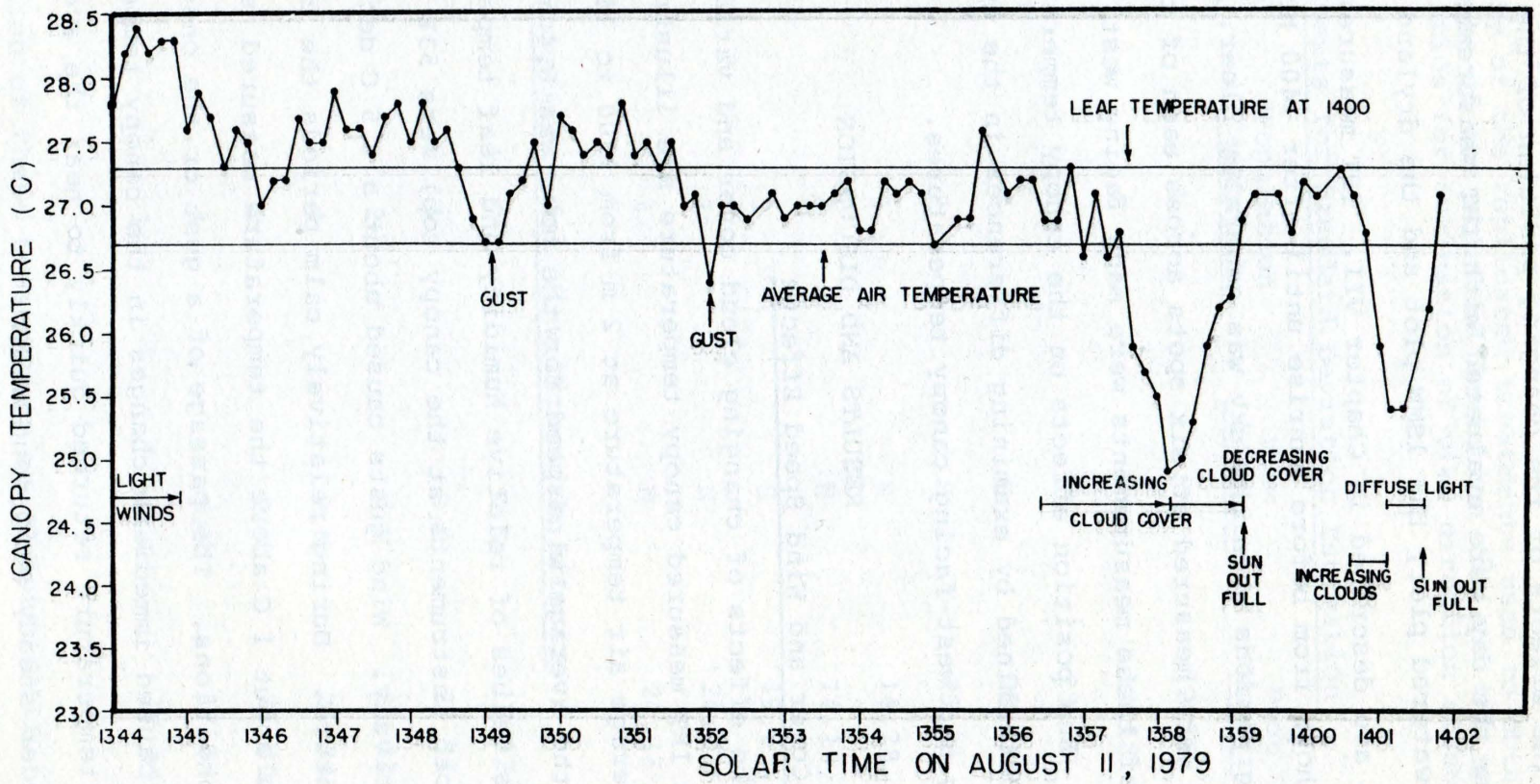


Fig. 3. Canopy temperature fluctuation in response to changing cloud cover and windspeed in a well-watered plot.

Decreases in solar radiation receipts caused by cloud passage resulted in a rapid decrease of about 2.0 to 2.5 C in canopy temperature. After passage of the cloud and return to full sunlight, recovery to the original canopy temperature required about a minute.

If canopy temperatures from one place are to be compared with those from another place they should be obtained under nearly constant solar radiation and windspeed conditions.

Nitrogen Stress Effects

On the three days of observation, the plot which received no nitrogen at planting was consistently 0.6 to 1.0 C warmer than any of the other nitrogen treated plots (Fig. 4). No other nitrogen treatments affected the crop temperature. This suggests that plant temperature becomes elevated only in severely nitrogen stressed plants. It is, therefore, possible that a severe nitrogen problem can interfere with the detection of water stress with an IRT. However, such severe nitrogen problems would probably never occur under normal farm managment, except in small areas where N fertilizer was inadvertently not applied.

These data suggest that nitrogen deficiencies could be monitored by infrared thermometers. This seems to be impractical, however, because the nitrogen stress became apparent to the eye before it became detectable through canopy temperature measurements.

View Direction Effects

The effect of north vs south view direction of the IRT on canopy temperatures was found to be significant (at the 95% level

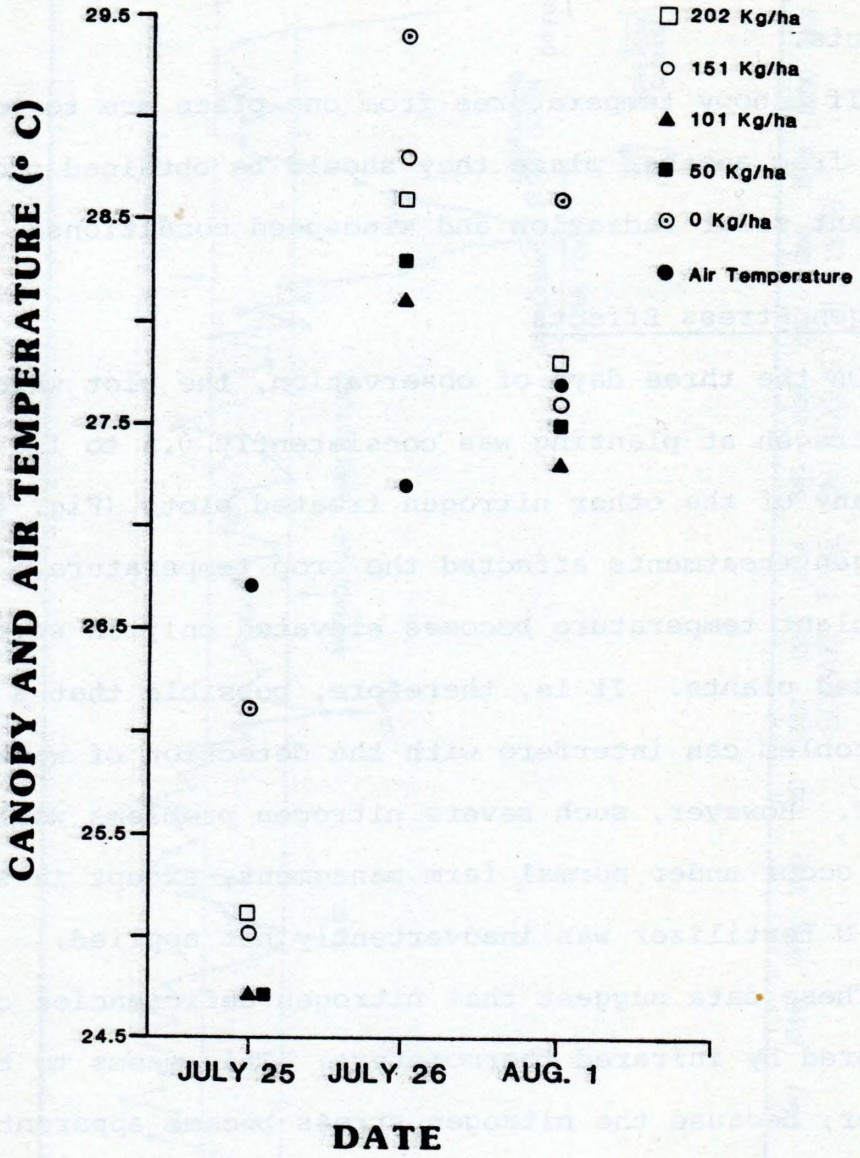


Fig. 4. Average canopy temperatures of plots fertilized at several levels of nitrogen. Readings taken near 1400 hours solar time. Air temperature at 2 m is also listed. Data are for July 25, 26 and August 1, 1979.

of probability) in certain of the plots in which water stress was allowed to develop (Table 2). Under well-watered or at low levels of water stress, there were no significant differences between the canopy temperatures obtained when the instrument was aimed north or south.

Although the effect of viewing direction was found to be significant in certain plots, caution must be exercised in interpreting these data. Plot to plot variation in temperature was observed in plots with identical water and population treatments viewed from the same direction. An example of this variation is given in Fig. 5 for plots 19 and 29. Differences in soil water holding capacities, uniformity of water application and other factors may affect the canopy temperature. Thus, differences in IRT canopy temperatures of identical population densities and water treatments may be due merely to environmental factors and not necessarily to the effects of viewing direction.

Even with these limitations, we still observed that canopy temperatures measured with north facing instruments were warmer than those measured with south facing instruments. This effect is illustrated in Figs. 6 and 7. Test statistics indicate that the canopy temperatures obtained when the IRT was aimed to the north were not significantly warmer than those obtained when aimed to the south in the well-watered (1.4) treatment but they were for the water-stressed (010) treatment.

These results suggest that the effect of view direction on mid-day canopy temperatures measured with an IRT was probably small enough to be neglected when plants were only minimally stressed for water. However, as water became more severely

Table 2. Test statistic of all plots matched by identical water treatment and population density with opposing view direction. Test statistic was calculated from Eq. 2. Significance at the 95% level is indicated by an asterisk.

Plot No.	Irrigation Treatment	Population Treatment	Test Statistic
15 & 32	010	2	3.31*
26 & 34	666	2	3.46*
26 & 34	666	4	1.78
23 & 34	666	4	1.61
25 & 30	616	2	0.24
17 & 33	1.4	1	0.44
17 & 24	1.4	1	1.19

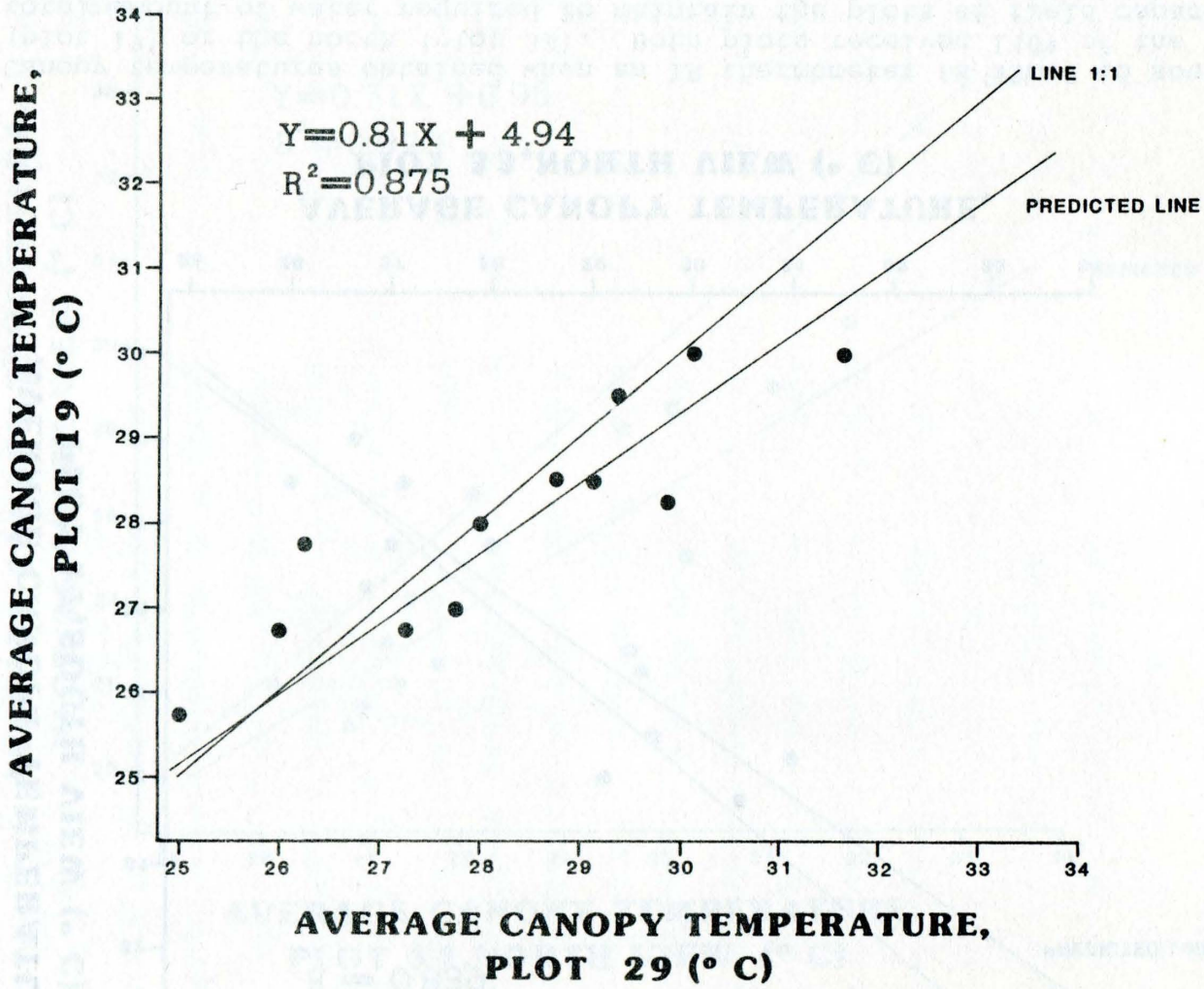


Fig. 5. Canopy temperatures obtained when an IR thermometer is aimed to the south on plots 29 and 19. Both plots received the same irrigation treatment and both had plant populations of 54,000 plants ha^{-1}. Data are for July 25 to August 31, 1979.

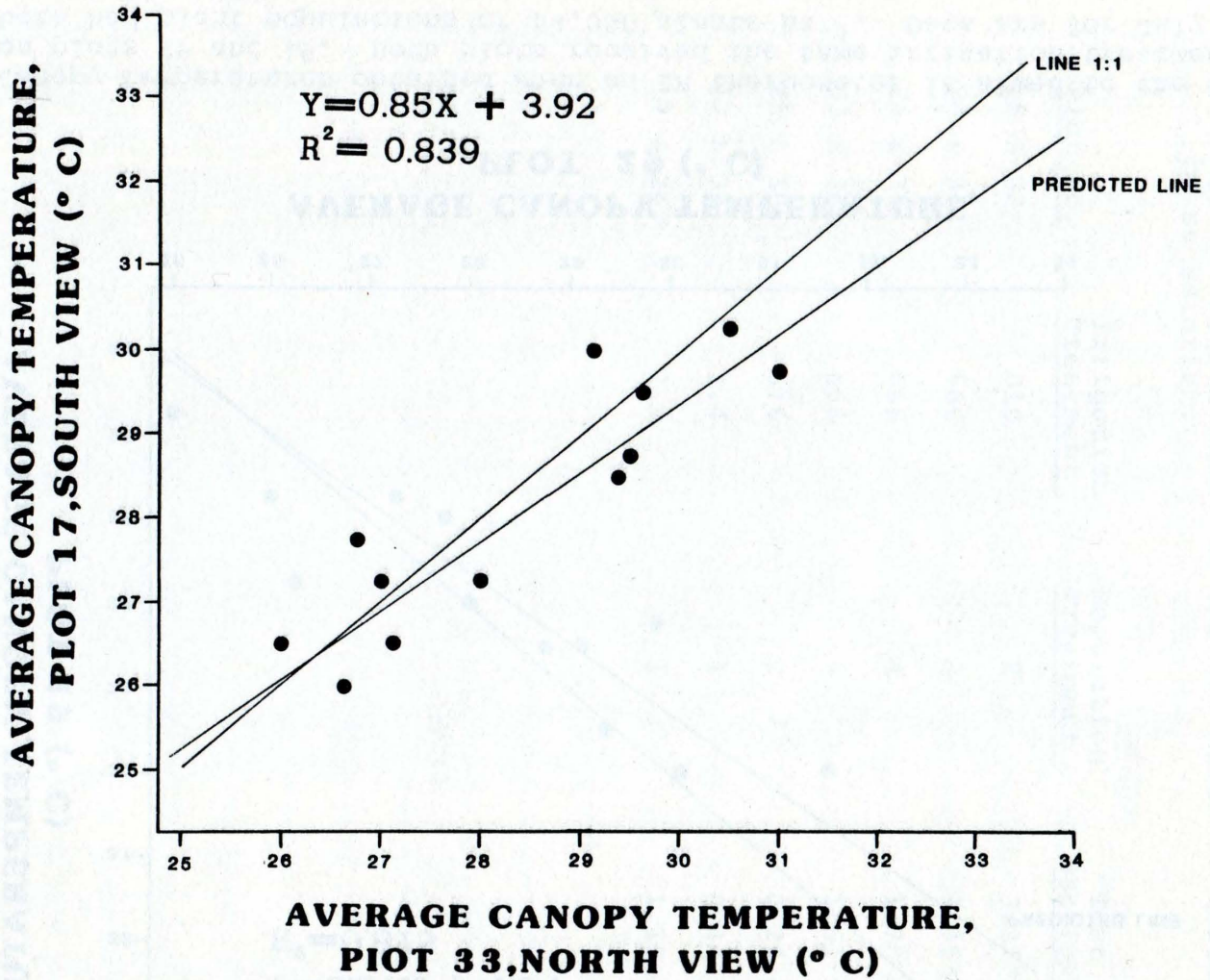


Fig. 6. Canopy temperatures obtained when an IR thermometer is aimed to south (plot 17) or the north (plot 33). Both plots received 140% of the total amount of water required to maintain the plots at field capacity. Plant population in both plots was 6,000 ha^{-1}. Data are for July 25 to August 31, 1979.

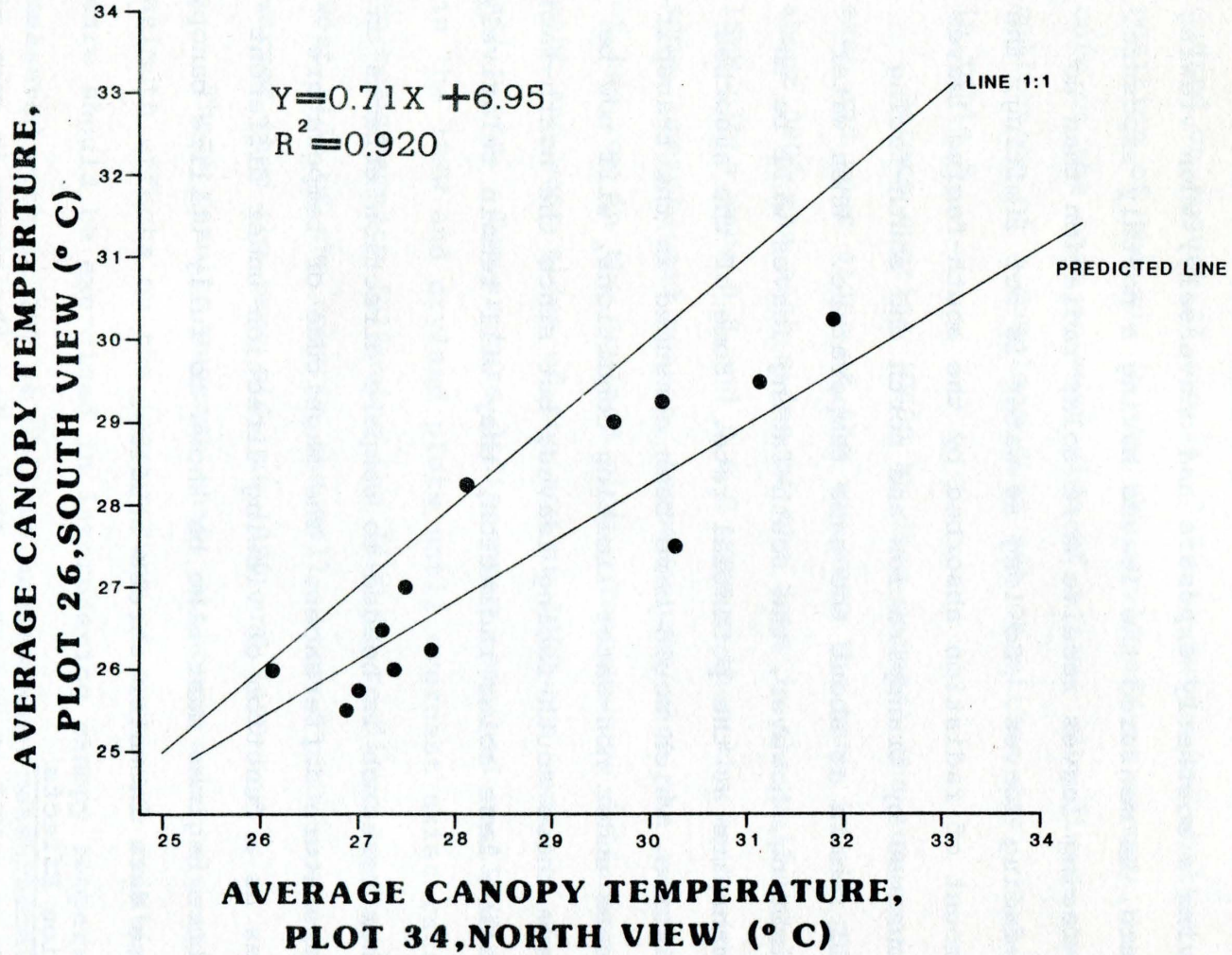


Fig. 7. Canopy temperatures obtained when an IR thermometer is aimed to the south (plot 26) or north (plot 34). Both plots were irrigated to field capacity during the pollination period but received no irrigation during the vegetative or grain-fill periods. Plant population in both plots was 36,000 plants ha^{-1}. Data are from July 25 to August 31, 1979.

limited, then the effect of view direction became important. A possible explanation for this follows: When viewing to the north, the observer measured the temperature primarily of the leaves having a southerly exposure and conversely, when viewing to the south, he measured the leaves having a northly exposure. The south-facing leaves receive more solar radiation than do the north-facing leaves. So long as water is not limiting, the greater amount of radiation absorbed by the south-facing leaves will be consumed by transpiration and north and south-facing leaves will remain at about the same temperature. When water becomes limiting, however, the south-facing leaves will be unable to transpire at the potential rate. Some of the absorbed solar radiation, which would have been consumed in the transpiration process under non-water limiting conditions, will now be used to warm these south-facing leaves, but since the north-facing leaves receive less solar radiation, they will remain relatively cool.

Further research is needed to compare direction effects on canopy temperature differences. The magnitude of temperature differences as a function of viewing direction under different soil moisture regimes must also be known to fully utilize canopy temperature data in water stress studies.

Sun Position Effects

In Chapter VII it was shown that, when the range in corn midday canopy temperatures within a plot exceeded 0.7, the need for irrigation was indicated. Because of the position of the sun in the sky, crop temperature measurements made with an obliquely held

IRT on north-south oriented rows before about 1000 or after about 1400 hrs solar time may show a greater temperature range because of differential heating of one side of a row. A study was conducted on August 23 and 24, 1979 to determine whether or not the position of the sun in the sky would affect canopy temperature of corn on the east or west side of a row. Cloudiness prevented the collection of a complete data set on either day. Results are given in Table 3.

Before sunrise (0600 hr data points) the temperatures on the east and west sides of the row were the same in all plots. By about 0900 the east sides of the rows in the well-watered and the lSMW plots were 0.8 and 0.6 C warmer than the west sides. For some, unexplained reason, temperatures were the same on both sides of the row in the dryland plot. Temperature differences between east and west sides of the row at 1000 hrs were 0.4 C or less in all plots. Temperature differences remained small (0.4 C or less) in the lSMW and dryland plots until overcast skies caused an end to measurements following the 1400 hr readings on August 24. The west side of the rows in the well-watered plot was about 0.6 C warmer than the east side at 1300 and 1400 hrs.

These results suggest that, although solar elevation and solar azimuth effects on the temperature of corn were relatively small, care should be exercised in interpreting canopy temperature data measured with an IRT at oblique angles when measurements are made before or after the 1000 to 1400 hr period. For example, the temperature differences caused by solar elevation and azimuthal effects on August 23 at 0900 in the well-watered plot were of sufficient magnitude to suggest that certain plants were under

Table 3. Comparison of canopy temperatures obtained from east and west side of corn rows in the dryland, well-watered and 1SMW plots. Data were obtained on August 23 and 14, 1979. Each temperature is the average of three readings.

		Well-Watered		1SMW		Dryland	
Date	Time	East	West	East	West	East	West
8/23	0600	11.7	11.7	11.9	11.9	12.0	12.0
8/23	0700	15.9	16.0	16.9	16.5	16.2	16.2
8/23	0800	18.6	18.5	19.2	18.8	19.8	19.6
8/23	0900	21.1	20.3	22.0	21.4	22.4	22.3
8/23	1000	23.1	22.7	23.1	22.7	24.1	24.4
8/24	1100	25.5	25.6	25.8	25.5	26.3	26.2
8/24	1200	25.1	25.0	26.0	25.8	27.3	27.2
8/24	1300	26.0	26.6	26.3	26.1	28.5	28.8
8/24	1400	23.8	24.4	24.6	24.3	25.9	26.3

*On August 23 skies were clear until about 1000 hrs. Cloud began building up and interfered with readings after 1000. On August 24 skies were almost clear during the 1100-1400 readings but become overcast before 1500.

very mild water stress but the 1200 to 1400 readings indicated that this was not so.

REFERENCES

Ansari, A. Q. and W. E. Loomis. 1959. Leaf temperatures. American J. of Bot. 46:713-717.

Clawson, K. L. 1980. Irrigation scheduling of corn utilizing infrared thermometry. Center for Agric. Meteorol. and Climatology, University of Nebraska-Lincoln, Progress Report 80-4, 139 p.

Clum, H. H. 1926. The effect of transpiration and environmental factors on leaf temperatures. I. Transpiration. American J. Bot. 13:194-230.

Curtis O. F. 1936. Leaf temperature and the cooling of leaves by radiation. Plant Phys. 11:343-364.

Edling, R. J., B. J. Barfield, C. T. Haan, and M. E. Fogleman. 1971. Prediction of leaf temperature under unstable atmospheric conditions. Trans. of the Amer. Soc. Agric. Eng. 14:1095-1099.

Fuchs, M., E. T. Kanemasu, J. P. Kerr, and C. B. Tanner. 1967. Effect of viewing angle on canopy temperature measurements with infrared thermometers. Agron. J. 59:494-496.

Gardner, B. R. 1980. Plant and canopy temperatures in corn as influenced by differential moisture stress. Center for Agric. Meteorol. and Climatology, University of Nebraska-Lincoln, Progress Report 80-1, 119 p.

Gates, D. M. 1964. Leaf temperature and transpiration. Agron. J. 56:272-277.

Gates, D. M. and W. Tantraporn. 1952. The reflectivity of deciduous trees and herbaceous plants in the infrared to 25 microns. Science 15:613-616.

Hsiao, T. C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Linacre, E. T. 1964. Calculations of the transpiration rate and temperature of a leaf. Archiv fur Meteorologie, Geophysik und Bioklimatologie, Ser. B., Vol. 13: 391-399.

Miller, E. C. and A. R. Saunders. 1923. Some observations on the temperature of the leaves of crop plants. J. Agric. Res. 26:15-43.

Norman, J. M. 1979. Modeling the complete crop canopy. In Modification of the Aerial Environment of Plants, B. J. Barfield and J. F. Gerber (eds.), ASAE Mono. 2, Amer. Soc. Agric. Eng., St. Joseph, Mich., pp. 249-277.

Stone, L. R., E. T. Kanemasu and M. L. Horton. 1975. Grain sorghum canopy temperature as influenced by clouds. Remote Sensing Environ. 4:177-181.

Waggoner, P. E. and R. H. Shaw. 1952. Temperature of potato and tomato leaves. Plant Physiology 27:710-724.

CHAPTER X

EVALUATING THE SEVERITY OF MOISTURE STRESS IN CORN UTILIZING REMOTELY SENSED CROP TEMPERATURE DATA

B. R. Gardner and B. L. Blad

ABSTRACT

Crop canopy temperature was measured with an infrared thermometer in four plots of corn subjected to different levels of water stress. The objectives of the research were (1) to measure crop canopy temperature at various times during the day in plots of corn subjected to different levels of water stress and to examine these data for evidence that the time of day at which large differences between well-watered and stressed vegetation (ΔT) begins is indicative of the severity of water stress and (2) to develop a stress severity index for quantifying the degree of water stress experienced by a crop.

We define a term called the stress severity index (SSI) where:

$$SSI = [(\Delta T_{a.m.})(\Delta T_{p.m.})]^{\frac{1}{2}}$$

For our $\Delta T_{a.m.}$ and $\Delta T_{p.m.}$ readings, we used data taken at 1000 and 1400 hrs solar time, respectively. Preliminary results indicate that an SSI value of zero with a postive $\Delta T_{p.m.}$ corresponds to mild or very moderate stress while an SSI value of five corresponds to severe stress. Examples of a plot with mild stress, two plots with moderate stress and one plot with severe stress were observed. A mid-morning and a mid-afternoon measurement of ΔT would seem to be very useful to accurately estimating the severity of crop water stress from crop temperature data. Further

research is needed to quantify the relationships between SSI values and the severity of crop water stress. Once these relationships have been developed, the use of the SSI or a similar approach should be useful for monitoring crop water stress from airborne or satellite-borne thermal scanners.

INTRODUCTION

Gardner et al. (Chapter V) reported that temperature differences (ΔT) between water stressed and non-stressed corn (Zea mays L.) do not, generally, develop before solar noon. In one experimental plot, however, positive ΔT values developed in the early morning. We postulated that the severity of stress may be indicated by the time of day at which stress develops. Severely stressed plants should exhibit positive values of ΔT in early or mid-morning while mildly to moderately stressed plants would develop positive values only after solar noon.

The major objectives of the research reported here were (1) to measure crop canopy temperature at various times of day in plots of corn subjected to different levels of water stress and to examine these data for evidence that the time of occurrence of large ΔT values may be indicative of the severity of water stress and (2) to develop a stress severity index for quantifying the degree of water stress experienced by a crop.

MATERIALS AND METHODS

Experiments were conducted at the Sandhills Agricultural Laboratory. Crop canopy temperatures were measured with a Telatemp Model Ag-42[1] infrared thermometer (IRT) at a viewing

[1]Telatemp Corp., P.O. Box 5160, Fullerton, CA (model Ag-42).

angle of approximately 20° from the horizontal. Measurements were made hourly between 0900 and 1500 hrs (solar time) on August 1 and August 3, 1979. ΔT values were determined by subtracting the average temperature of row 2 in plots 1 through 11 from the average temperature in plot 35 or the temperature of row 22 in plots 6, 8, 10 (Fig. 1). Row 2 data provide the average temperature of fully irrigated plants. Row 2 data are from water stressed plants. Plot 35 was a dryland plot in the plant population study which was very severely stressed for water.

RESULTS AND DISCUSSION

Prior to solar noon on August 1, 1979, ΔT was found positive only for plot 35 (Fig. 2). By 1400 hours ΔT was positive in plots 8, 10 and 35. On August 3, 1979, ΔT was positive at 1000 hours in all plots except plot 6 and by 1400 it was positive in all plots (Fig. 3). It seems that the level of stress was increasing with time in the four non-irrigated plots. The severity of stress was highest in plot 35 on both dates. In plot 6 no stress was evident on August 1 but by August 3 some plants were beginning to experience stress in that plot.

In order to use crop temperature data to quantify stress level, we have defined a term called the stress severity index (SSI), as a function of ΔT, where:

$$SSI = [(\Delta T_{a.m.})(\Delta T_{p.m.})]^{\frac{1}{2}}$$

We selected ΔT readings at 1000 and 1400 hours solar time for the a.m. and p.m. readings, respectively. There may be better times, especially the a.m. reading, which may be chosen should

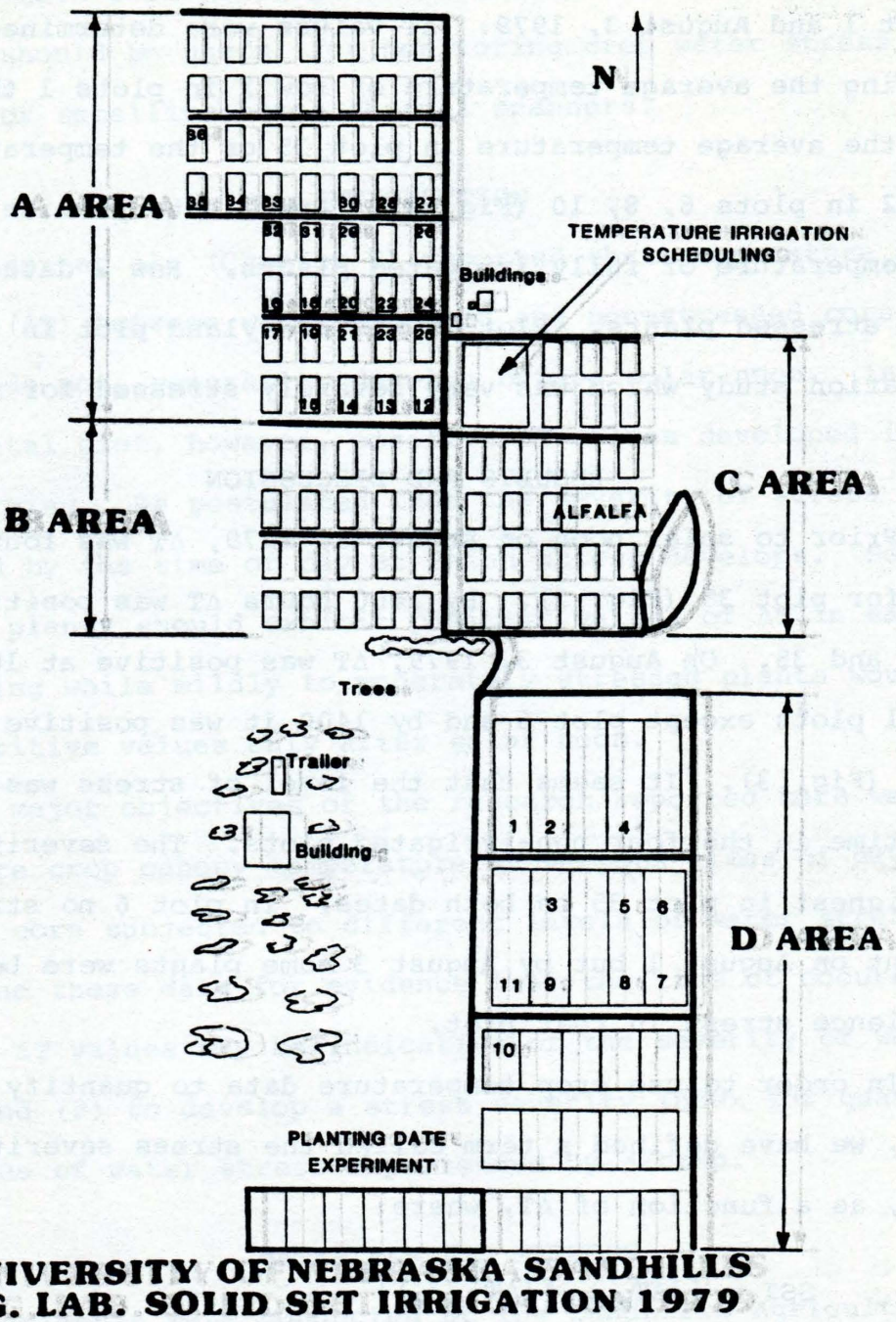


Fig. 1. Location of plots used in moisture stress severity study. Plots used in study are numbers 1-11 and 35.

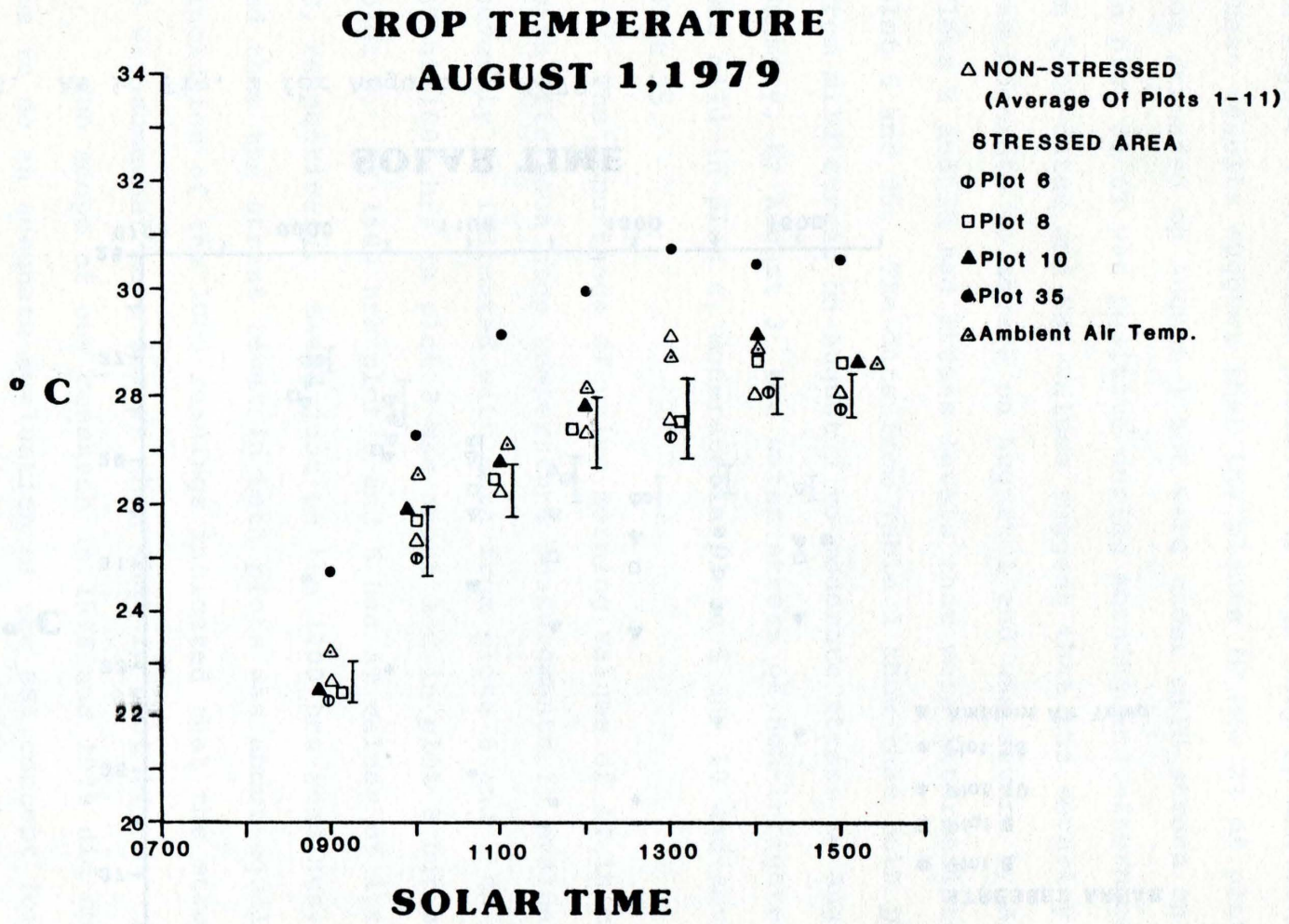


Fig. 2. Crop temperature of corn in four water stressed plots and the average of 11 non-stressed plots during 0900-1500 hrs on August 1, 1979. The bars indicate the range in temperature of the well-watered plots.

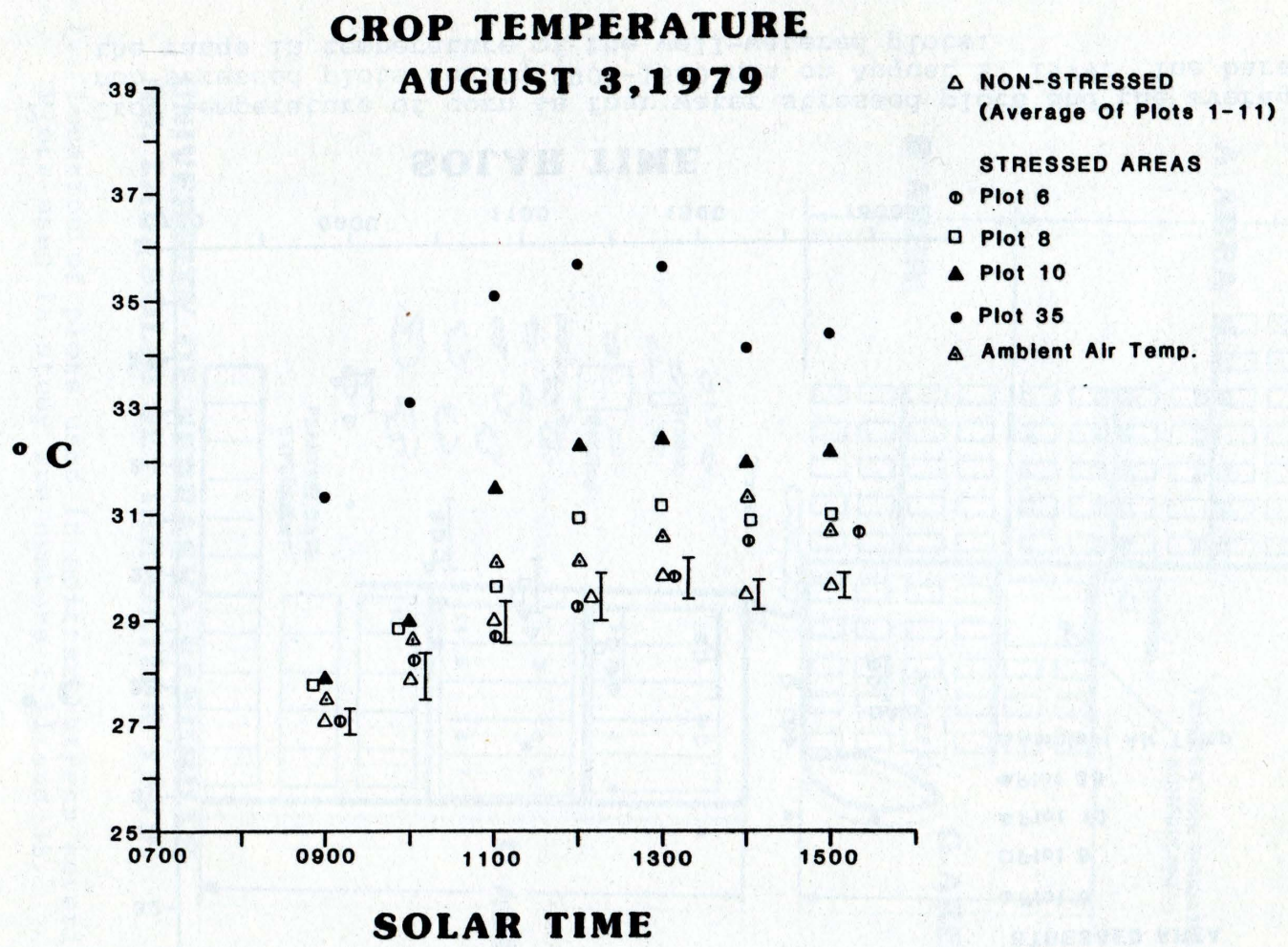


Fig. 3. As in Fig. 2 for August 3, 1979.

further study indicate the desirability of doing so.

SSI values for the four plots we evaluated are in Table 1. In plot 6 morning and afternoon ΔT values were zero on August 1. On August 3 ΔT became positive in sign only by mid-afternoon. These results suggest that the plants in row 22 of plot 6 were not stressed on August 1 but were under mild stress on August 3. In plot 35 ΔT was positive during morning and afternoon periods on both dates and SSI values suggest that the severity of stress was moderate to severe on August 1 and was severe by August 3. Plots 8 and 10 had stress levels that were intermediate between plot 6 and 35. The data from Table 1 show that both plots went from mild stress on August 1 to moderate stress by August 3. In summary, by August 3 the water stress of non-irrigated plants was mild in plot 6, moderate in plots 8 and 10 and severe in plot 35.

The importance of using morning values of ΔT in conjunction with afternoon crop temperature measurements to evaluate stress severity is indicated with data from plots 6 and 8 on August 3. ΔT at 1000 hrs in plot 8 was about 1 C in plot 8 but zero in plot 6. At 1400 hrs plot 8 and 6 had ΔT values of 1.4 and 1.0 C, respectively. Based just on the 1400 hrs readings, it appeared that the stress level in both plots was about equal. However, inclusion of the 1000 readings indicated that the stress in plot 8 was somewhat more severe than that in plot 6.

The scope of our research in 1978 and 1979 did not permit us to do an adequate evaluation of the SSI concept for estimating crop water stress. We are confident that the SSI approach or something similar will be very useful in monitoring crop water

Table 1. Stress Severity Index (SSI) values for four non-irrigated plots, where:

$$SSI = [(\Delta T_{mid\text{-}morning})(\Delta T_{mid\text{-}day})]^{\frac{1}{2}}$$

ΔT is the difference in temperature (C) between an irrigated and non-irrigated area. Mid-morning and mid-day values were computed for 1000 and 1400, respectively.

	ΔT		August 1	ΔT		August 3
Plot	1000	1400	SSI	1000	1400	SSI
6	0	0	0.0	0	1.0	0.0*
8	0	0.7	0.0*	0.8	1.4	1.1
10	0	1.2	0.0*	1.1	2.5	1.7
35	1.9	2.4	2.1	5.1	4.6	4.8

*Stress levels were mild to moderate since only $\Delta T_{p.m.}$ was positive.

stress with temperature data from airborne or satellite-borne thermal scanners. Further research is needed, however, to quantify relationships between SSI values and the severity of crop water stress.

Preliminary analysis of our data suggests that an SSI value of zero in conjunction with a positive $\Delta T_{p.m.}$ value corresponds to mild or, perhaps, very moderate stress. An SSI value approaching five indicate severe stress. It is uncertain, at this time, whether or not a given SSI value will correspond to a given stress level. It appears certain, however, that SSI values can be used to compare the relative level of stress from one field to another. Measurements of plant water stress, including plant water potential and stomatal diffusive resistance, are needed in conjunction with crop canopy temperature measurements for the major agronomic crops before the SSI concept can be adequately evaluated.

Since fluctuations in various environmental conditions can cause variation in mid-day ΔT measurements, we suggest that mid-morning ΔT measurements will aid in the interpretation of the mid-day canopy temperature data. In fact, mid-morning and a mid-afternoon measurement of ΔT is essential if crop temperature data are to be used for accurate estimation of the severity of crop water stress.

CHAPTER XI

EVALUATION OF THE FEASIBILITY OF USING MULTISPECTRAL DATA TO ASSESS MOISTURE STATUS IN CORN

B. L. Blad, B. R. Gardner and K. L. Clawson

ABSTRACT

The reflectance or emittance of electromagnetic radiation from a cropped surface is influenced, among other things, by the moisture status of the crop. The principal objective of the research reported here was to determine whether or not spectral data from any of eleven visible, near infrared or thermal infrared wavebands of a multispectral scanner on a NASA airplane could be used to detect water stress in corn (Zea mays L.). A second objective was to evaluate whether or not hail damage in corn could be detected from the multispectral data.

The hail damaged corn reflected more radiation in the visible and less in the near infrared and thermal infrared portions of the electromagnetic spectrum than did the undamaged corn. The effects of hail damage were still detectable on the imagery several weeks after the damage occurred.

Data from the thermal channel showed differences between the water-stressed and non-stressed corn. Temperature gradients were clearly evident on the thermal imagery of plots with soil water gradients.

The variability of the scanner data on a given plot appeared to be greater than the temperature variability detected from ground based measurements. This was thought to be caused, for the most part, by differences in the viewing angles of the aircraft and based instruments. The scanner aboard the aircraft viewed at an

almost vertical angle. This permitted the detection of radiation emitted from the soil, while the infrared thermometer on the ground viewed the plots at oblique angles so that essentially only vegetation was seen. The use of thermal imagery to detect crop water stress looks promising.

There was a slight, but detectable, increase in reflected visible and near infrared radiation with an increase in water stress of the corn. These changes were so small that they may not be useful for quantifying crop water stress. Certainly, the response of corn to water stress was more easily detected with the thermal data. Additional studies of the effects of water stress on reflected and emitted radiation in the visible, near infrared, middle infrared and thermal infrared portions of the electromagnetic spectrum are recommended.

INTRODUCTION

The reflectance or emittance of electromagnetic radiation from a cropped surface is influenced by several biological and physical factors including crop type, percent crop cover, plant biomass, plant architecture, plant water status, the flux density of impinging radiation, solar elevation, etc. The response of vegetation to incident radiation is a function not only of environmental and plant conditions, but also of the wavelength of the radiation incident upon the plant. Hoffer (1978) summarizes certain of these responses as follows: "Distinct differences are found among the visible, near infrared and middle infrared portions of the spectrum. In the visible wavelengths, the pigmentation of the leaves is the dominating factor. Most of the

incident energy is absorbed and the remainder reflected. The internal structure of the leaves control the level of reflectance in the near infrared where about half of the energy is reflected, nearly half is transmitted and very little is absorbed by the leaf. The total moisture content of the vegetation controls the middle-infrared reflectance, with much of the incident energy being absorbed by the water in the leaf, the remainder being reflected."

Therefore, moisture stress should cause changes in the reflective and emissive characteristics of vegetation and it should be possible to detect moisture stress by remote sensing techniques. This is especially true if instrumentation is available for detecting spectral signatures in relatively narrow and discrete wavebands. Research has demonstrated that the reflectance of vegetation is affected, among other things, by plant water status (Knipling, 1970; Meyers, et al., 1970; Woolley, 1971; Blum et al., 1978; Tucker, Elgin and McMurtrey, 1979).

Other chapters in this report deal almost exclusively with responses of vegetation to water stress as indicated by the radiation emitted in the thermal infrared waveband. There is much yet to be learned about the spectral responses of various kinds of vegetation and the factors which influence spectral response patterns. The primary purpose of this study was to determine whether or not spectral data from any of eleven visible, near infrared (NIR) and thermal infrared wavebands of a multispectral scanner carried aboard a NASA aircraft can be used to detect water stress in corn (Zea mays L.). A second objective was to evaluate the potential of these data for detecting hail damage

to a corn crop.

The instrument aboard the NASA aircraft was used to collect data only in the visible, near infrared and thermal infrared portions of the spectrum. No observations were made of the middle-infrared region. A brief summary of studies which provide insight into expected changes in reflectance due to moisture stress in the visible and NIR regions of the electromagnetic spectrum follows.

Hoffer and Johansen (1969) showed that changes in the reflectance of individual corn leaves did not occur in either the visible or NIR regions until the moisture content of the leaves had fallen below 66%. After this point, there was a steady increase in reflectance in both the visible and NIR as leaf moisture content declined. Sinclair (1971) found a detectable increase in reflectance in the NIR from sorghum leaves as they decreased from 76% to 73% water content.

These laboratory studies indicate that reflectance in the visible and NIR spectrum can be expected to increase as water stress increases in severity. The magnitude of these increases should be relatively small, but detectable.

The results from field studies are not so clear. Tucker (1979, 1980) reported that reflectance in the 0.63-0.69 μm range (visible red) increased with decreasing leaf water content in corn and soybean canopies. Reflectance in the 0.75-0.8 μm (NIR) range, however, decreased with decreasing leaf water content.

Decreases in NIR reflectance due to moisture stress in the field appear to contradict the findings of laboratory measurements. This apparent contradiction may be explained, however.

Meyers et al. (1970) showed that NIR reflectance from cotton leaves was strongly dependent on the number of leaf layers. NIR reflectance decreased by nearly 50% as the number of leaf layers was reduced from 6 to 1. The reason for the decreased reflectance with decreased numbers of leaf layers is illustrated in a diagram from Hoffer (1978)(Fig. 1). In his model leaves reflected 50% and transmitted 50% of the incident NIR radiation. An increase in moisture stress should cause an increase in NIR reflectance of individual leaves. If moisture stress results in loss of leaves, however, NIR reflectance from a canopy would decrease. It is, therefore, conceivable that NIR reflectance measurements in field crops may increase, decrease, or show no change because of moisture stress.

MATERIALS AND METHODS

Experiment Site

This experiment was conducted in 1979 in the solid set irrigation area at the University of Nebraska Sandhills Agricultural Laboratory (SAL), located near Tryon, Nebraska (41° 37' N; 100° 50' W; 975 m above mean sea level). Interpretation of the multispectral data obtained at SAL requires an understanding of the general nature of several experiments conducted concurrently (Fig. 2).

The north-eastern portion (A-area) was devoted to a large-scale moisture stress experiment on corn. The plots in A-area were subjected to varying degrees of stress throughout the growing season. Details of irrigation and plant population treatments on several of these plots are given in Fig. 1 of Chapter VIII.

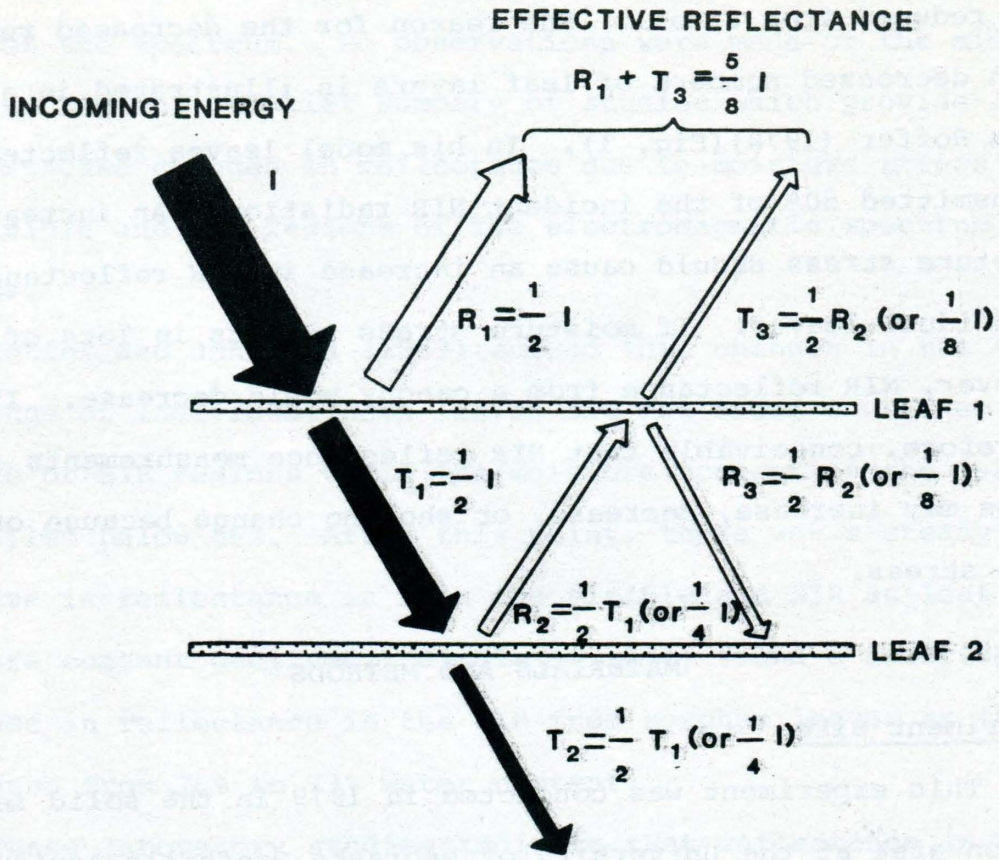


Fig. 1. Simplified sketch of the effect of multiple-leaf layers on vegetative reflectance. I = incoming energy; T = transmitted energy; R = reflected energy (from Hoffer, 1978).

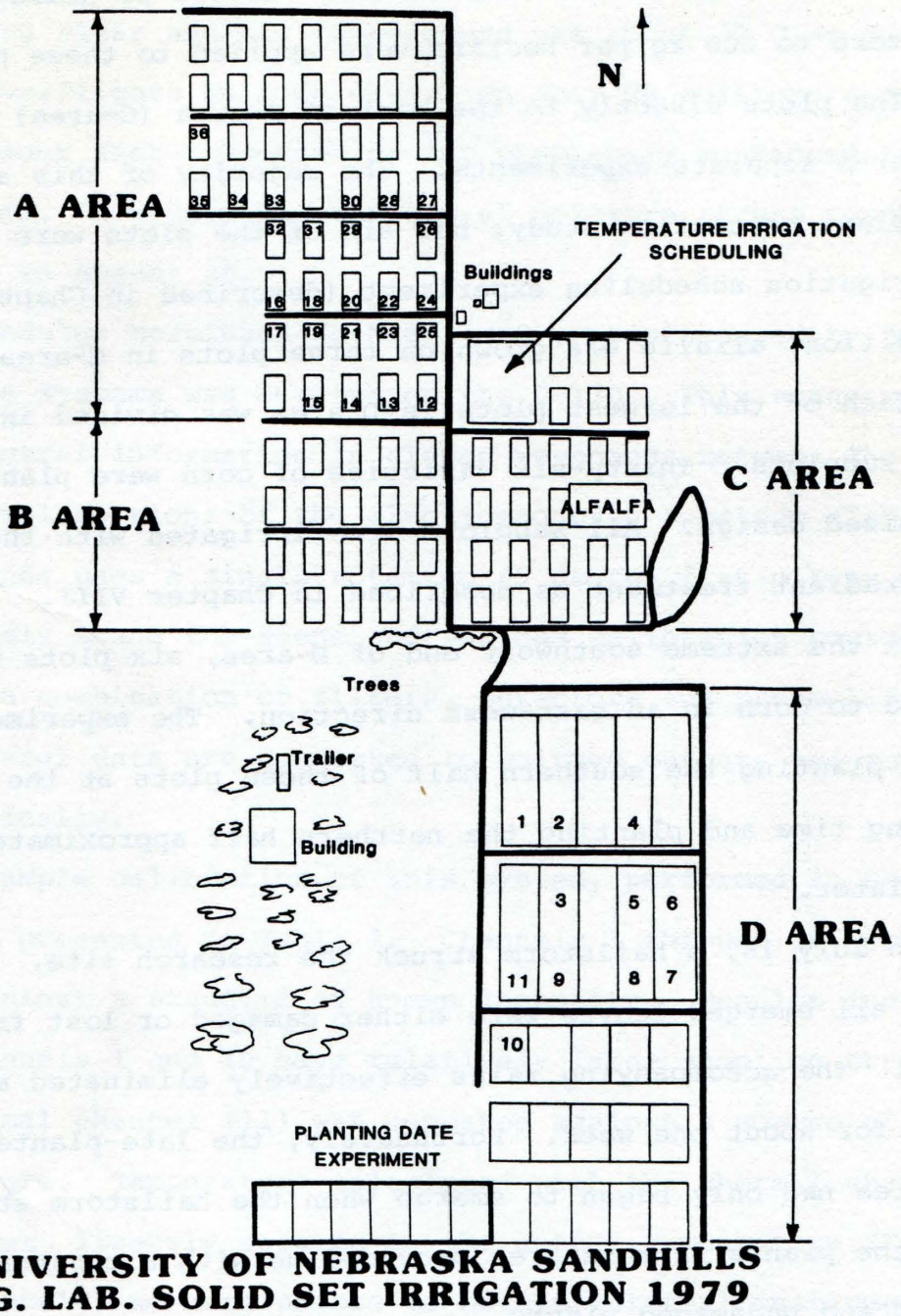


Fig. 2. Location of all plots in the solid set area at the Sandhills Agricultural Laboratory. Numbered plots were used in crop temperature studies.

B-area, directly to the south of A-area, was devoted primarily to a nitrogen application experiment. Levels of nitrogen ranging from zero to 200 kg per hectare were applied to these plots.

The plots directly to the east of B-area (C-area) were used for three separate experiments. The majority of this area was part of a plant population study, but six of the plots were devoted to an irrigation scheduling experiment (described in Chapter VII). In addition, alfalfa was grown on three plots in C-area.

Each of the largest plots in D area was divided into seven small subplots. Thirty-six varieties of corn were planted in a randomized design. All subplots were irrigated with the GIG moisture gradient treatment as described in Chapter VIII.

At the extreme southwest end of D-area, six plots were planted to corn in an east-west direction. The experiment involved planting the southern half of these plots at the normal planting time and planting the northern half approximately one month later.

On July 16, a hailstorm struck the research site. Virtually all emerged leaves were either damaged or lost from the plants. The accompanying rains effectively eliminated moisture stress for about one week. Fortunately, the late-planted corn in D-area had only begun to emerge when the hailstorm struck. Thus, the plants in this area provided us with a constrast between damaged and undamaged plants.

Multispectral Data

An instrumented C-130 aircraft from the NASA headquarters at the Johnson Space Center in Houston, Texas, flew at an altitude

of 500 m over the experiment site twice in 1979. Data were collected at 1100-1130 hrs (solar time) on July 20 and August 30. Skies were clear and air temperature was about 30 C at the time of the overflights on both days. On July 20 moisture stress was only a minor factor because of the previously mentioned hail and rain storm. A widely ranging set of moisture stress conditions occurred on August 30.

A Modular Multiband Scanner (M^2S), manufactured by Bendix Aerospace Systems was carried on the C-130. This scanner collects multispectral information in eleven wavebands between the visible and thermal portions of the electromagnetic spectrum (Table 1). The scanner uses a single rotating 45 degree flat mirror which alternately scans the scene and various calibration sources. Through a combination of filters, detectors and preamplifiers, the spectral data are converted to voltage outputs and recorded electronically.

A sample calibration of this system, performed in December, 1975, is presented in Table 2. Channels 1 through 10 were compared against a standard of known intensity. Results indicate that channels 1 and 10 have relatively large sampling errors. The thermal channel (11) was compared against a source of known temperature. Temperature calculated with the thermal channel output was linearly related to the actual temperature (Fig. 3). Unfortunately, we were unable to obtain internal instrument temperature calibration data during the time of the flight. Thus, we cannot directly assign temperature values directly to the data from channel 11.

Table 1. The eleven channels used in the Bendix Modular Multiband Scanner.

Channel	Waveband Interval (μm)
1	0.42 to 0.46
2	0.46 to 0.50
3	0.50 to 0.54
4	0.54 to 0.58
5	0.58 to 0.62
6	0.62 to 0.66
7	0.66 to 0.70
8	0.70 to 0.74
9	0.77 to 0.86
10	0.96 to 1.04
11	7.89 to 11.60

Table 2. Sample calibration of the Bendix Modular Multiband Scanner, December 3, 1975, comparing the average and standard deviation of 100 consecutive scan lines of a laboratory standard.

Channel	Signal Average	Signal Standard Deviation
1	89.42	7.2095
2	83.44	1.4335
3	71.112	0.86052
4	66.367	0.67986
5	70.459	0.60481
6	82.29	0.73195
7	101.38	0.75585
8	138.61	0.74914
9	163.86	1.0248
10	134.20	5.3295

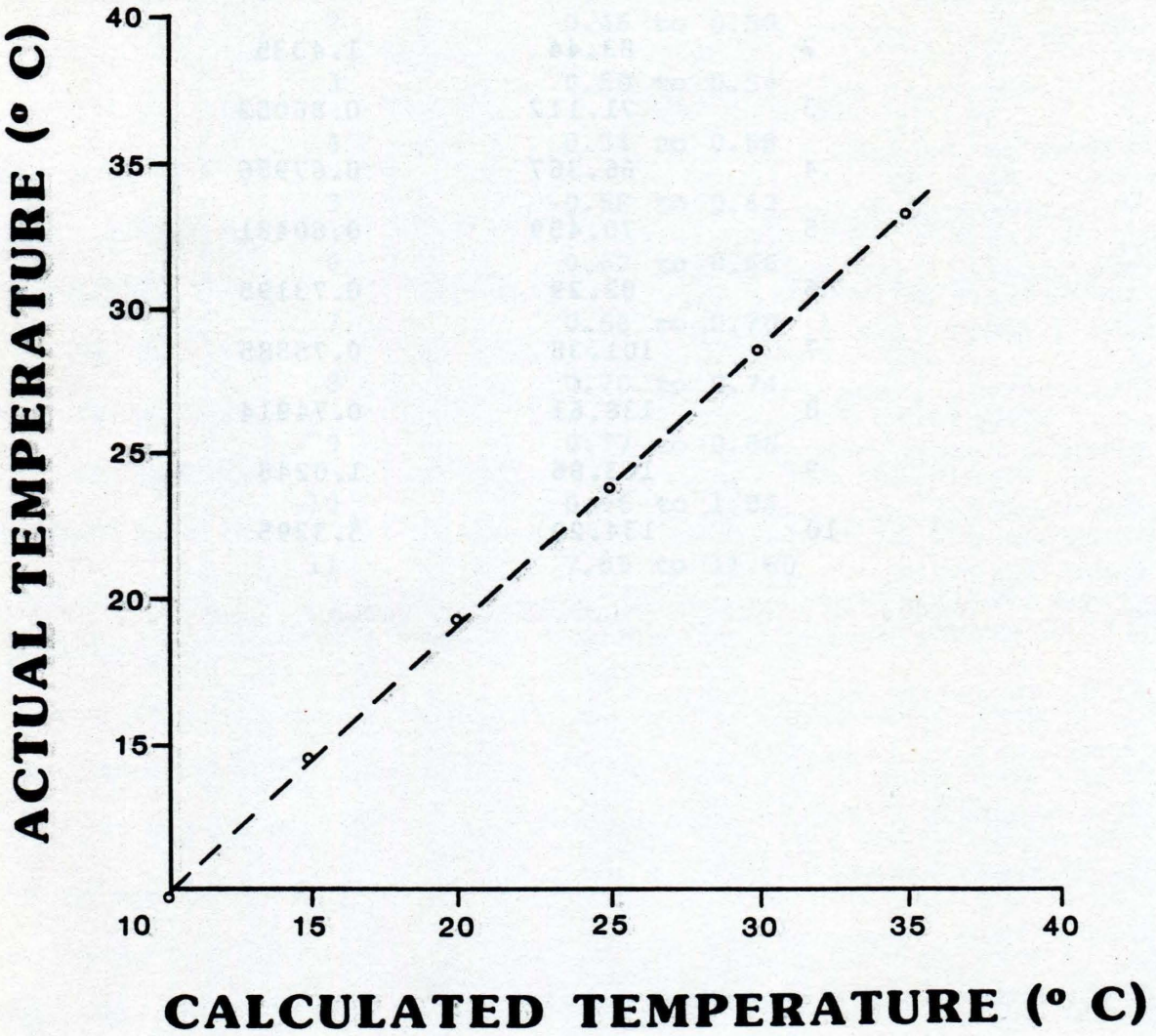


Fig. 3. Comparison of the actual temperature and the temperature calculated with signals from the thermal channel (channel 11) on the M^2S carried on the NASA airplane.

Ground Based Data

During the times of the NASA overflights, observers on the ground made observations of crop temperature with a Telatemp Model AG-42 Infrared Thermometer (IRT) at sample sites in A-, C- and D-areas.

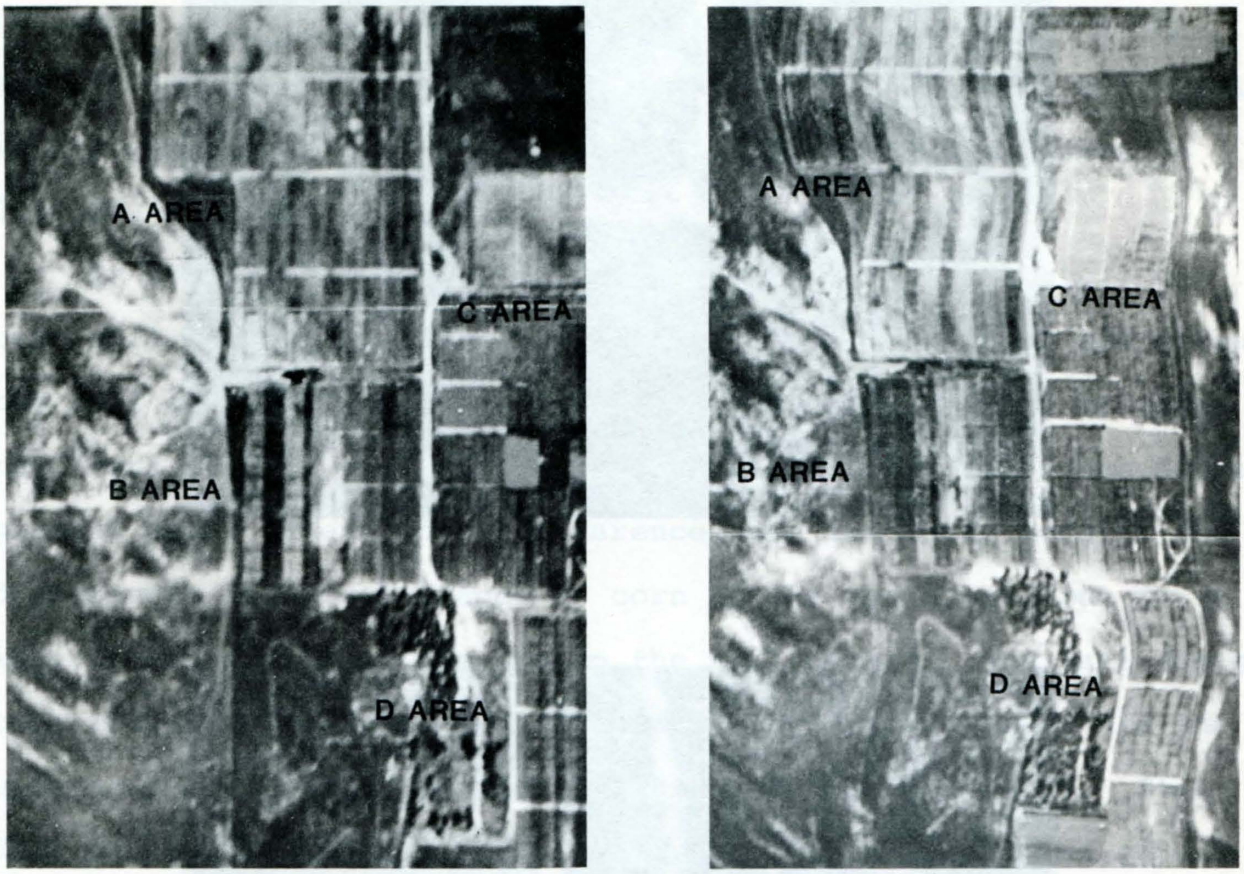
Statistical Analysis of Data

The computation of means and variances for reflected radiation was performed on a pixel by pixel basis for each channel of data. A pixel was approximately one meter square in size. At least 300 pixels were used to compute each statistic. With so many samples, relatively small differences in reflectance values due to various treatments can be shown to be statistically significant.

RESULTS AND DISCUSSION

Data from channels 4, 6 and 10 were used to make a composite image of the experimental area on both overflight dates (Fig. 4). One of the characteristics of the spectral imagery from A-area is an alternating striped effect. This effect is caused by nitrogen treatments in this area. Nitrogen fertilizer was applied only to the treatment plots. None was applied to the areas between the plots. The between plot areas were nitrogen deficient so that the corn was yellowed and stunted in growth.

On July 20, the contrast between corn (labeled E) and bare soil (labeled L) on the east-west plots at the south end of D-area as seen from a photographic enlargement of this area (Fig. 5) is unmistakable. By August 30, both area L and area E had



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Fig. 4. Three band color composite of the Sandhills Agricultural Laboratory on July 20 and August 30, 1979. Color assignments were: Blue - Channel 4; Green - Channel 6; Red - Channel 10. Due to the high cost of reproducing color photographs, the ones shown here are reproduced only in black and white. North is to the top of the page.

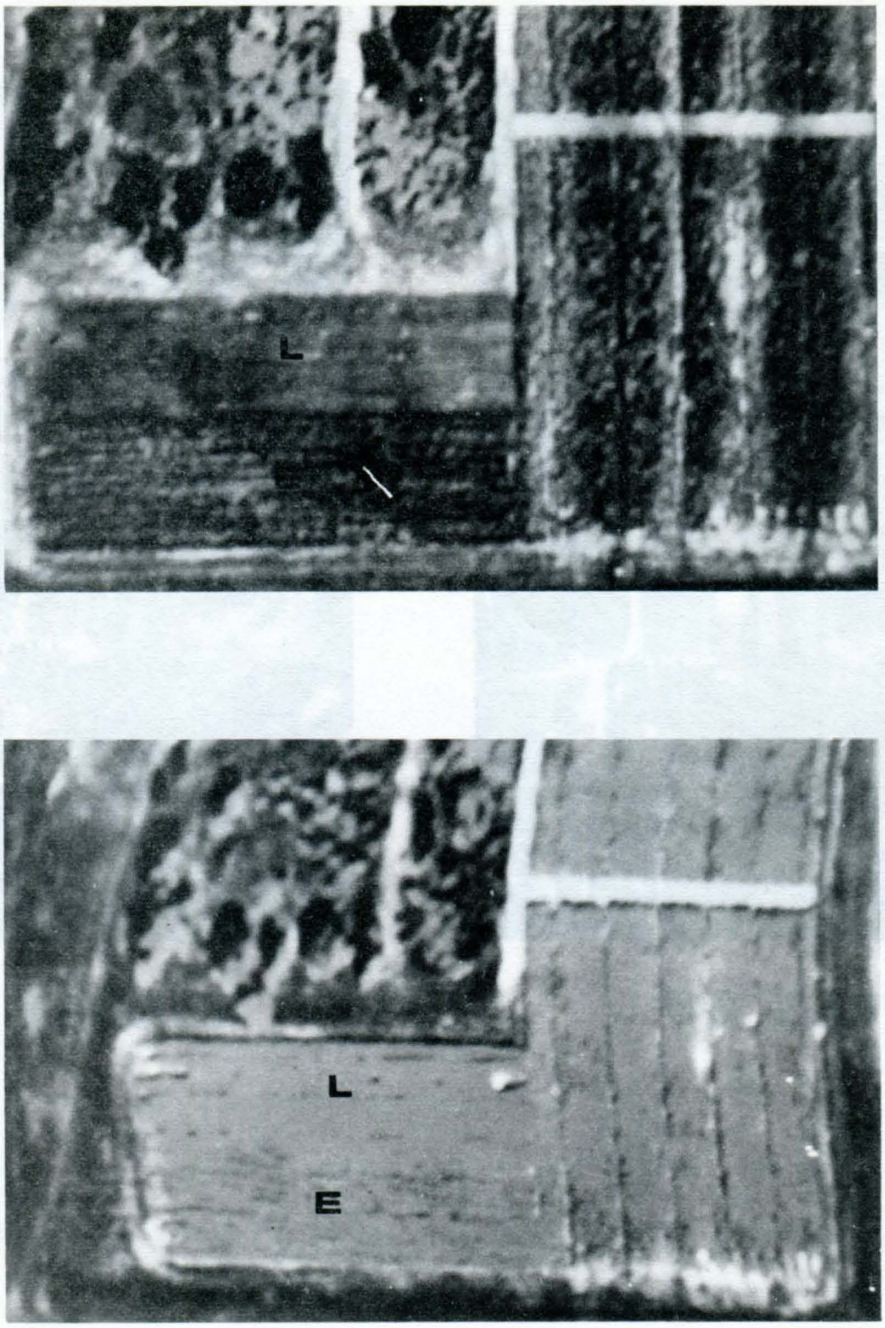


Fig. 5. Enlarged color composite of the south end of D area, showing the contrast between bare soil and a corn crop on July 20 (A) and August 30, (B) 1979. Color assignments were the same as in Fig. 4. Area L is late planted corn and area E is early planted corn.

complete vegetative cover. There was still a distinct difference between the radiation reflected from these two areas.

The patterns observed on these two dates are explained as follows. Except for channels 9 and 10 the light-colored sandy soil at SAL produced higher flux densities of reflected radiation in all channels than did the corn which covered the surface on July 20, 1979 (Table 3).

By August 30, the situation had changed considerably. The bare soil area was now completely covered by corn which had escaped the hail damage. This late-planted area showed up as a brighter red (more uniform gray) on the color composite than did the earlier-planted area. These color differences may indicate, merely, the differences in growth stages of corn in the two areas, but it is more likely that they are due to the hail damage. The hail damaged corn reflected 5-12% more radiation in channels 1-7 than did the undamaged corn and 5-15% less in channels 8-11 (Table 4). Standard deviation was also consistently lower in the damaged corn. This decrease in variability may be due to an increase in the spectral roughness of the hail damaged plot. A spectrally rough surface acts as a diffuser of incoming radiation which, in turn, reduces the variability in reflectance measurements. These results suggest that multi-spectral imagery in the visible and NIR waveband should be useful in delineating areas subjected to hail damage even though several weeks may have elapsed between the time at which the damage occurred and the time when the imagery was obtained.

The effect of hail damage on the thermal radiation sensed by the airborne scanner is shown in the histograms given in

Table 3. Comparison of the relative energy measured in the 11 MS channels from bare soil and corn on July 20, 1979.

		Bare Soil		Corn	
Channel	Wavelength (μm)	Average Signal	Standard Deviation	Average Signal	Standard Deviation
1	0.42 - 0.46	70.76	± 7.91	48.72	± 4.99
2	0.46 - 0.50	58.42	± 6.17	39.74	± 3.09
3	0.50 - 0.54	43.45	± 3.74	32.36	± 2.09
4	0.54 - 0.58	41.38	± 3.00	32.88	± 2.02
5	0.58 - 0.62	37.53	± 3.30	27.94	± 1.79
6	0.62 - 0.66	36.54	± 4.03	24.65	± 1.98
7	0.66 - 0.70	40.83	± 4.74	26.68	± 2.31
8	0.70 - 0.74	64.39	± 3.77	60.97	± 3.93
9	0.77 - 0.86	89.97	± 9.66	120.91	± 11.34
10	0.96 - 1.04	121.10	± 9.14	143.27	± 11.06
11	7.89 - 11.60	87.86	± 5.84	75.18	± 5.67

Table 4. Comparison of the relative energy measured in the 11 M^2S channels from hail damaged and undamaged corn on August 30, 1979.

		Damaged Corn		Undamaged Corn	
Channel	Wavelength (μm)	Average Signal	Standard Deviation	Average Signal	Standard Deviation
1	0.42 - 0.46	44.57	± 4.91	40.27	± 5.23
2	0.46 - 0.50	39.40	± 2.32	34.65	± 2.72
3	0.50 - 0.54	33.61	± 1.72	31.15	± 2.43
4	0.54 - 0.58	31.81	± 1.61	30.46	± 2.90
5	0.58 - 0.62	27.84	± 1.41	25.42	± 2.10
6	0.62 - 0.66	27.97	± 1.43	24.77	± 1.79
7	0.66 - 0.70	28.54	± 1.59	24.94	± 1.93
8	0.70 - 0.74	60.17	± 3.57	63.58	± 6.83
9	0.77 - 0.86	145.49	± 10.27	170.81	± 20.47
10	0.96 - 1.04	165.99	± 10.68	184.18	± 20.15
11	7.89 - 11.60	71.85	± 7.14	75.07	± 8.27

Fig. 6. The irrigated corn plot undamaged by hail was slightly cooler than the hail-damaged plot but the major effect was the large difference in canopy temperature variability. Both the slightly higher average temperature and the greater temperature variability are due, for the most part, to the sensing of radiation from the warm exposed soil in the hail damaged plots. It seems apparent from the large number of points at relative intensity values above 100 in the damaged plot that the radiation value measured in certain of the pixels was dominated by thermal radiation from the soil surface.

Thermal imagery of plots used in the irrigation scheduling experiment (C-area) is given in Fig. 7 for both dates of overflight. On July 20, 1979, little temperature difference was noted between any of the plots although a greater proportion of darker (cooler) areas are apparent in the fully irrigated plot (4) than in the dryland plot (5). Histograms show that values of the relative intensity of thermal radiation were greater for the dryland plot than for the irrigated plot (Fig. 8). This suggests that the dryland plots were slightly warmer. Unfortunately, actual average scanner temperature differences could not be calculated for comparison with the average ground temperatures of 26.2 C in plot 4 and 26.3 C in plot 5. That the ground based temperature differences are small is not surprising since they were made in areas of these two plots showing essentially identical shades of gray (Fig. 7). There appears to be more temperature variability on July 20 in the irrigated plot (4) than in the dryland plot (5). Since it had rained on July 16, we did not expect to observe large temperature differences or a great temperature

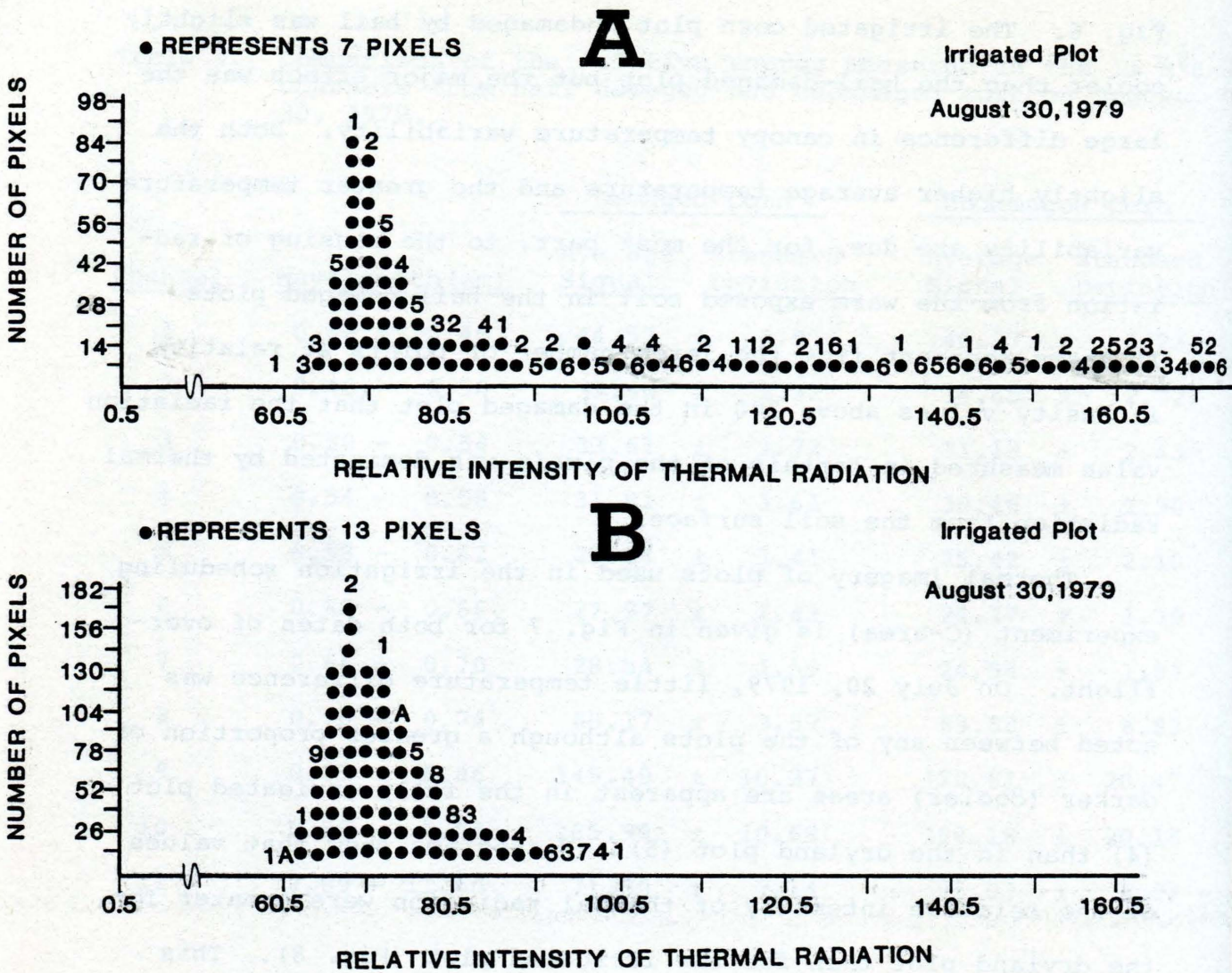


Fig. 6. Histograms of data from channel 11 (7.9-11.6μm) on August 30, 1979, at about 1115 hrs. solar time. A. Data from the hail-damaged plot (E). B. Data from undamaged plot (L). Both plots were fully-irrigated.

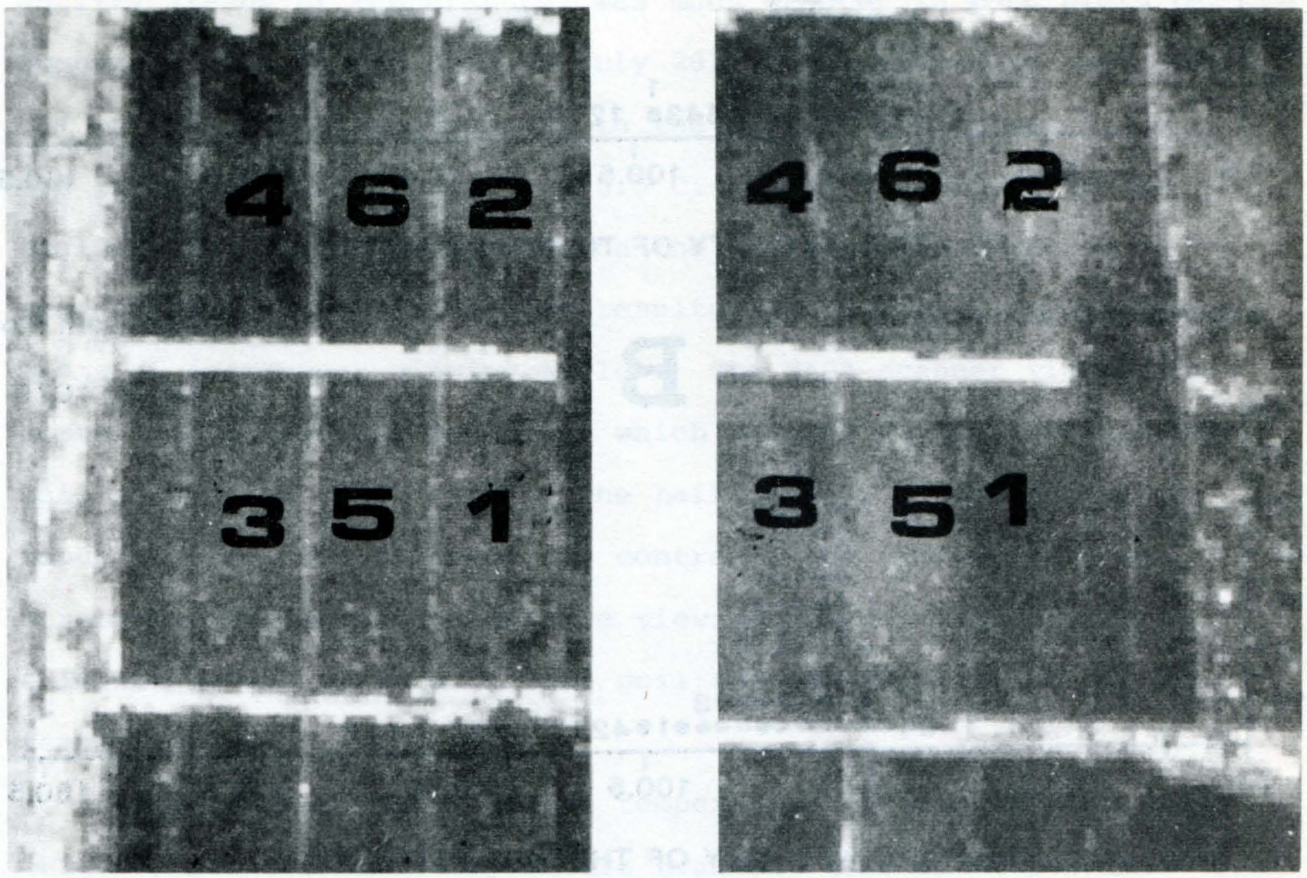


Fig. 7. Thermal imagery (channel 11) for the Irrigation Scheduling plots (C area) on July 20 and August 30, 1979. The light colored lines running E-W are roadways between plots. Those running N-S are sprinkler lines between plots. Areas 1, 2, 3, 4, 5 refer to plots receiving different irrigation treatments (Chapter VII). The darker the color, the cooler the temperature.

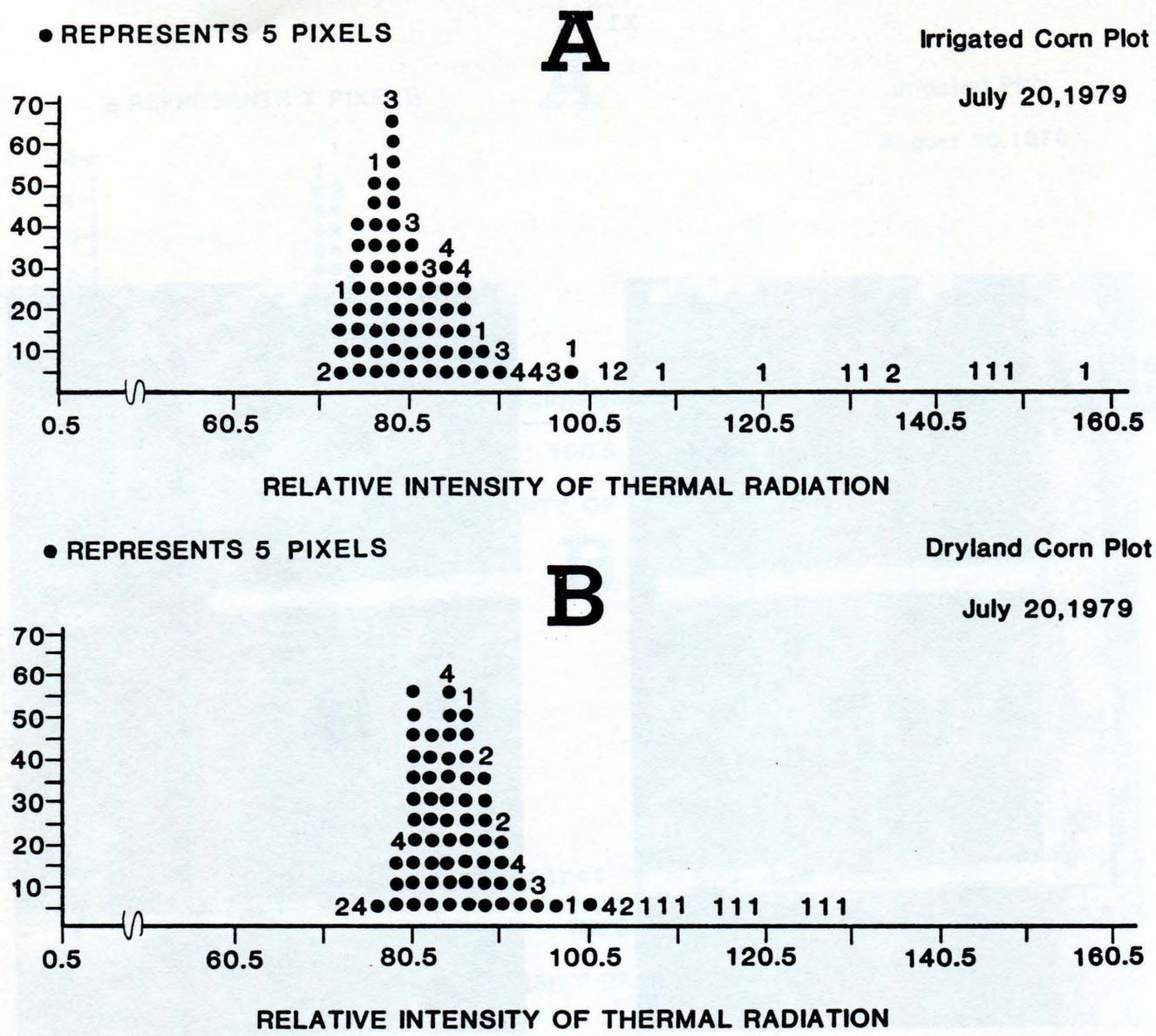


Fig. 8. Histograms of data from Channel 11 (7.9-11.6μm) on July 20, 1979, at about 1115 hrs. solar time. A. Data from plot 4 (neutron probe scheduled plot). B. Data from plot 5 (dryland plot).

variability within any of the plots by July 20.

On August 30, 1979, the thermal imagery (Fig. 7) and the histograms (Fig. 9) show that the irrigated plot was definitely cooler (darker) than the dryland plot. The temperature variability (range of temperature) was much greater in both plots on August 30 than it had been on July 20. The temperature variability of the ground measurements in the irrigated plot was 0.7 C and in the dryland plot it was 0.5 C. These variabilities are smaller than would be expected on the basis of the airborne scanner data. These divergent results are best explained on the basis of instrument viewing angles. The NASA scanner viewed the plots from a vertical position, which allowed it to view exposed soil as well as crop. Due to the hail damage, a substantial amount of soil was exposed. By contrast, the ground based measurements were made from oblique viewing angles, essentially eliminating any effects of bare soil on observed crop canopy temperatures.

Careful examination of the temperature pattern in plot 6 (Fig. 7) shows that a temperature gradient existed across this plot on August 30, 1979, but not on July 20. The lowest temperatures were on the west side (left) and the warmest on the east side. These data are displayed as histograms in Fig. 10. A large range in temperature within plot 6 is evident in the August 30 histogram. At least eight pixels show thermal radiation values at each intensity interval in the range of 70 to 110 units with a number of pixels in the range up to 170 units. This rather broad range of values is due, not only to the differences in plant temperatures caused by the various levels of water stress, but also

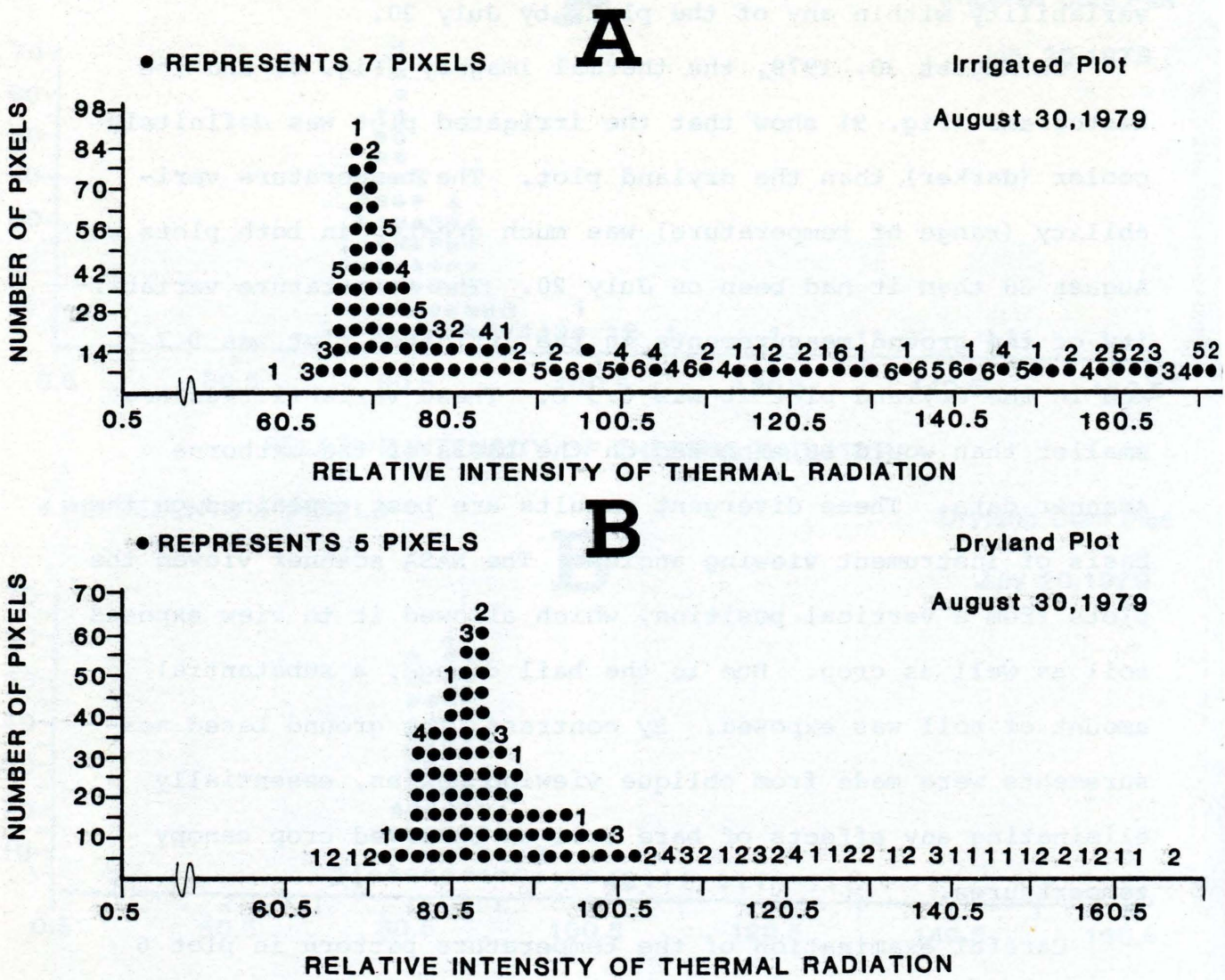


Fig. 9. As in Fig. 8 for August 30, 1979.

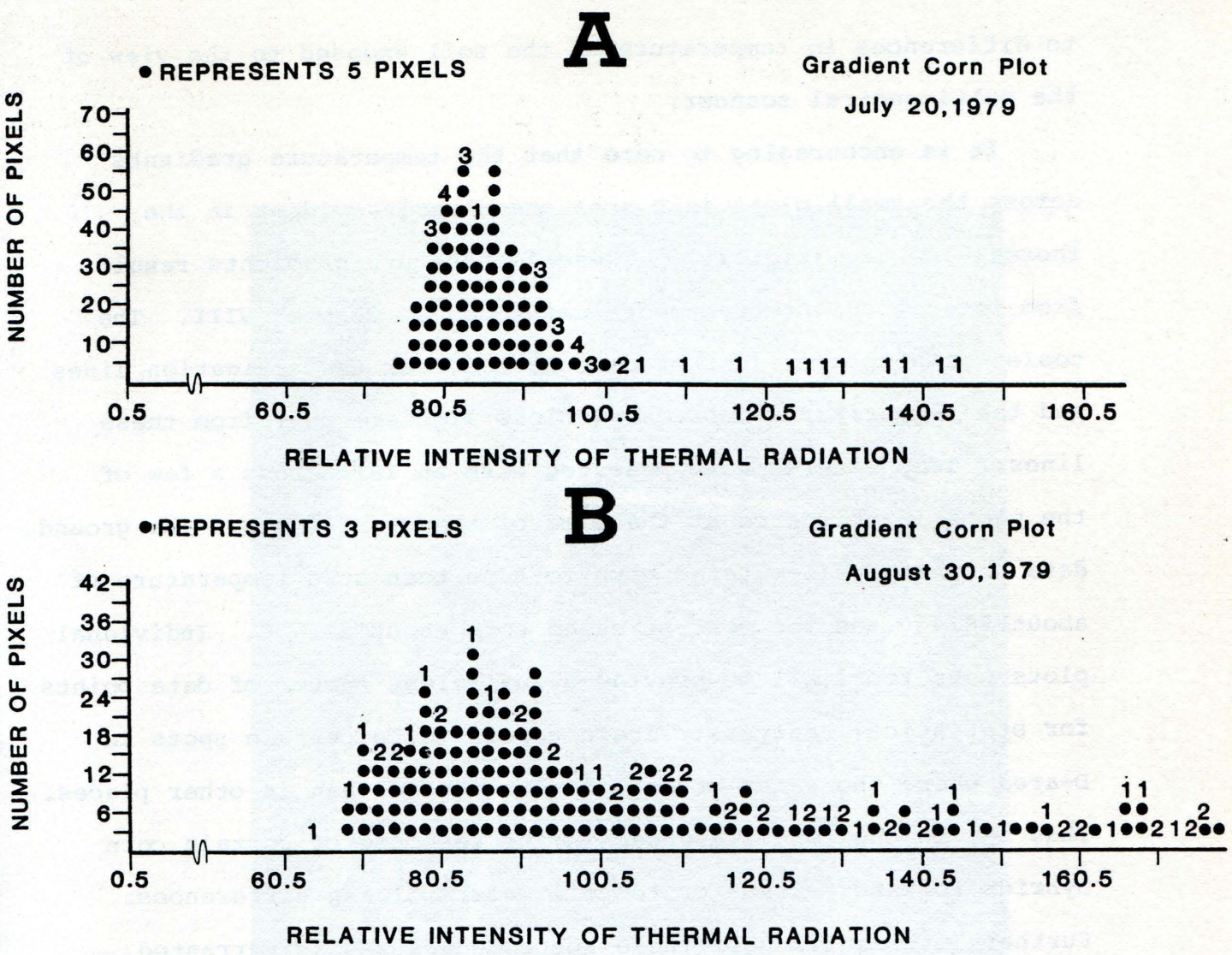


Fig. 10. Histograms of data from Channel 11 (7.9-11.6μm) on July 20 (A) and August 30, (B) 1979 at about 1115 hrs. solar time from plot 6 (gradient plot).

to differences in temperature of the soil exposed to the view of the multispectral scanner.

It is encouraging to note that the temperature gradients across the small plots in D area are clearly evident in the thermal imagery (Fig. 11). These temperature gradients result from water gradient treatments described in Chapter VIII. The cooler temperatures (darker colors) are near the irrigation lines and the temperatures increase (colors lighter) away from these lines. Temperatures were measured with an IRT across a few of the plots in this area at the time of the overflights. The ground data show the well-watered corn to have been at a temperature of about 28.4 C and the most stressed corn about 31.6 C. Individual plots were too small to provide a sufficient number of data points for statistical analysis. There appear to be certain spots in D-area where the water stress is more severe than in other places. This may be due to differences in the response of certain corn hybrids to water stress or to soil water holding differences. Further investigation of these suspected causes is warranted.

The overflights were made 2 to 3 hours before the time of day when maximum crop canopy temperature differences due to water stress are expected. Thus, the observed temperature differential between well-watered and stressed vegetation was smaller during the time of the overflight than if they had been made around 1400 hrs. Nevertheless, temperature differences at 1115 hrs were readily detected in the thermal imagery - a promising finding. Further studies are needed to evaluate and quantify crop temperatures-plant water status relationship and to further elucidate the relationships between crop canopy temperatures measured at

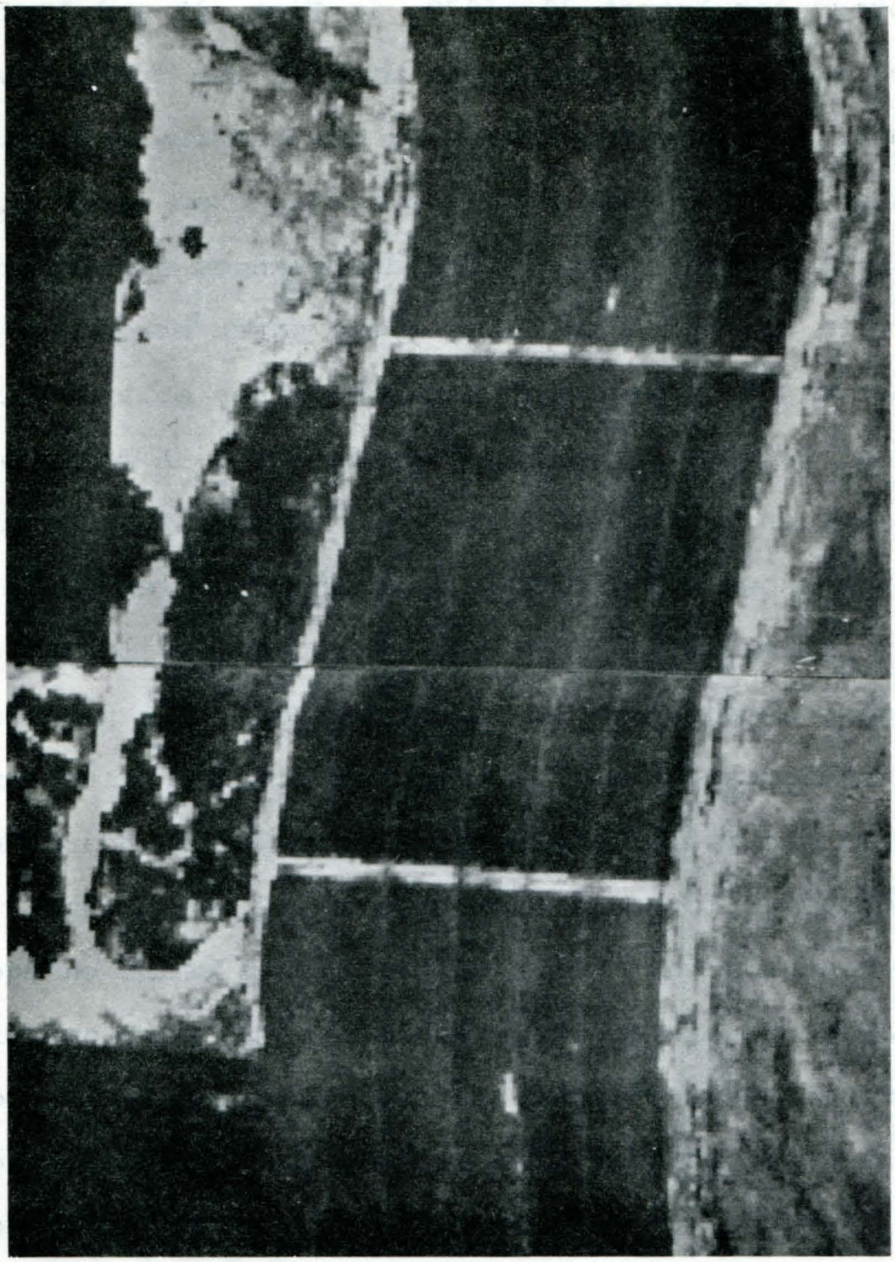


Fig. 11. Thermal imagery (Channel 11) of the water gradient treatments in area D on August 30, 1979. The two thin lines running N-S to the right and left of the center of the field are the irrigation sprinkler lines. The water gradients are applied on either side of these lines.

the surface and those made from airborne platforms.

In order to evaluate whether or not visible and NIR radiation might also aid in the detection of plant water stress, data are plotted for August 30, 1979, in Figs. 12 and 13 for channels 1-10 for each of the five plots used in the irrigation scheduling experiment. A slight increase in the average reflectance value in each of the channels with increasing crop water stress is apparent in these figures. The differences are probably too small, however, to be useful in quantifying water stress in corn.

The very different reflectance values obtained in the 3 SMW plot (plot 2) can be explained as follows. A third or half of plot 2 lies in a problem area. The exact nature of the problem is not yet known but the area does show up clearly on imagery from all channels on August 30. (See Fig. 14 for an example of the imagery obtained.) It is undoubtedly this problem area which causes the large changes in crop reflectance values and which results in the rather large differences in standard deviation values observed for data from several of the channels.

We conclude that water stress causes small changes in the reflectance of corn in the visible and NIR portions of the spectrum. Since these changes are small, we feel that crop water stress is detected much more readily from thermal imagery. We do feel, however, that further studies of the influence of water stress on reflection of radiation from cropped surfaces are warranted. These studies should involve selected wavebands in the visible, NIR, middle infrared, and the thermal infrared regions of the spectrum.

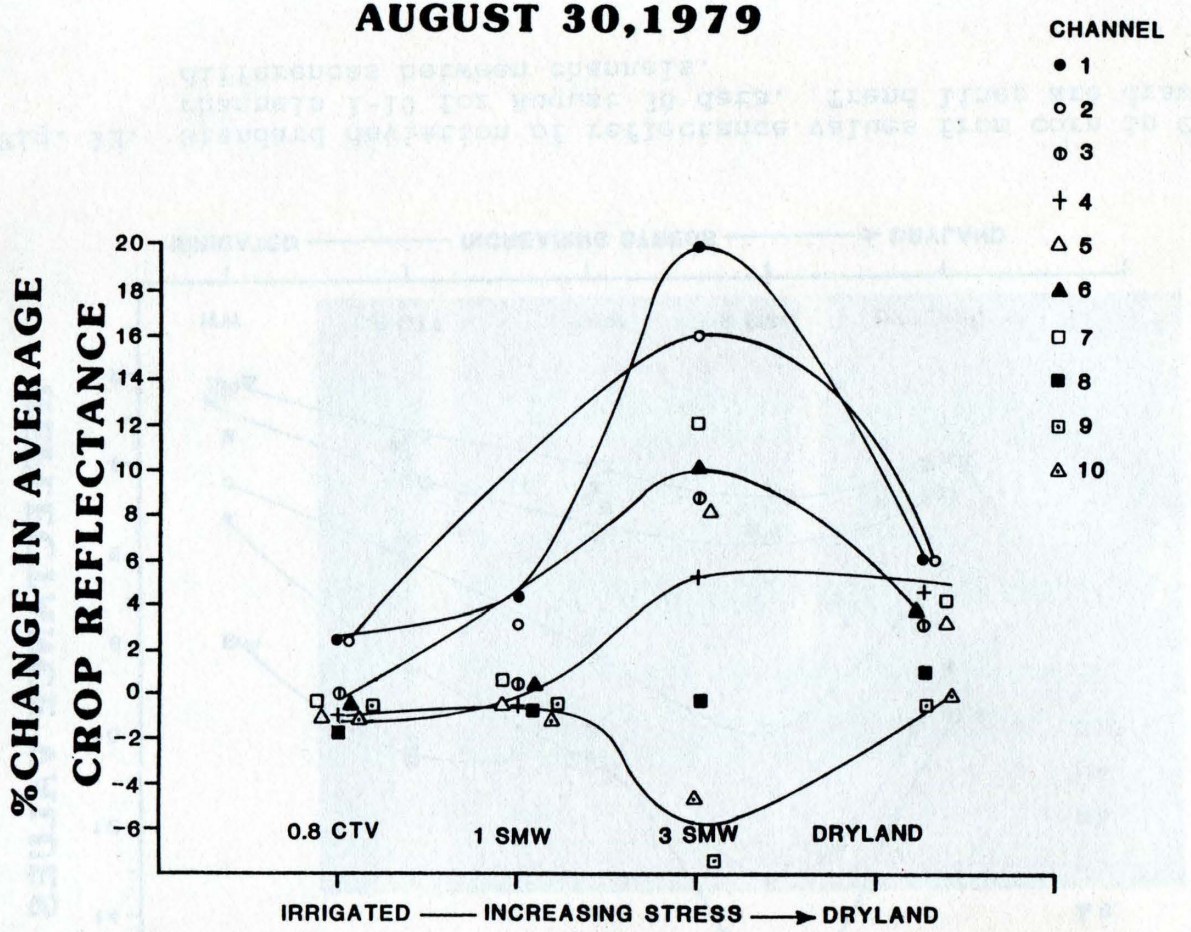


Fig. 12. Increasing stress change in average corn reflectance in channels 1-10, as a percent of the reflectance from irrigated plots on August 30, 1979. Trend lines are drawn to clarify differences between channels.

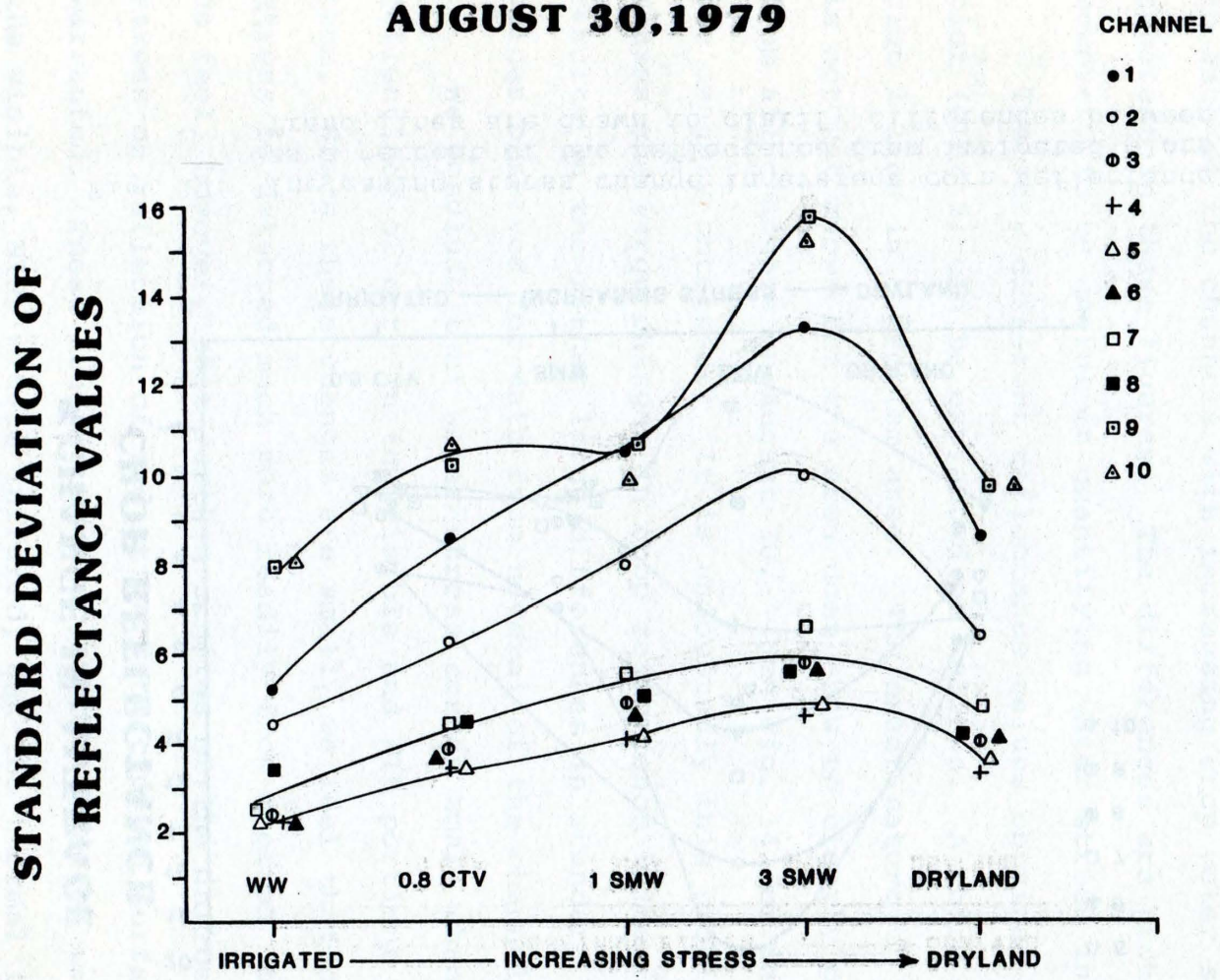


Fig. 13. Standard deviation of reflectance values from corn in C area in channels 1-10 for August 30 data. Trend lines are drawn to clarify differences between channels.

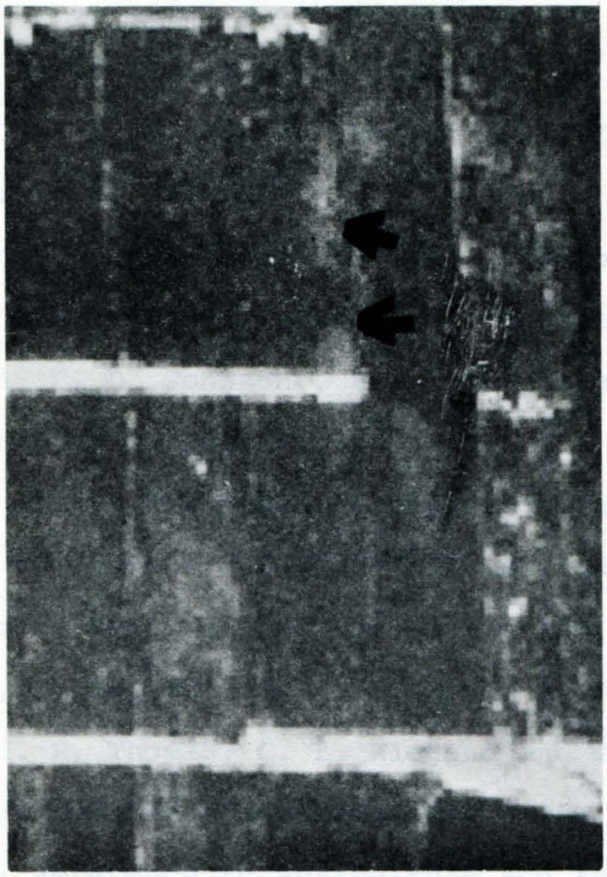


Fig. 14. Imagery from the temperature irrigation scheduled plots in C area. Data are from Channel 6 (0.62-0.66μm range) on August 30, 1979. The arrows show the problem area in the 3SMW plot (plot 2).

REFERENCES

Blum, A., K. R. Schertz, R. W. Tobler, R. I. Welch, D. T. Rosenow, J. W. Johnson and L. E. Clark. 1978. Selection for drought avoidance in sorghum using aerial infrared photography. Agron. J. 70:472-477.

Hoffer, R. M. 1978. Biological and physical considerations in applying computer-aided analysis techniques to remote sensor data. In: Remote Sensing the Quantitative Approach. eds. P. H. Swain and S. M. Davis. McGraw-Hill, Inc. New York, N. Y. Chap. 5, p. 227-289.

Hoffer, R. M., and C. J. Johannsen. 1969. Ecological Potentials in Spectral Signature Analysis. In: Remote Sensing in Ecology. ed. P. L. Johnson. Univ. of Georgia Press, Athens, Georgia. Chapter 1, pp. 1-29.

Knipling, E. B. 1970. Physical and physiological basis for the reflectance of visible and near-infrared radiation from vegetation. Remote Sensing Environ. 1:155-159.

Meyers, V. I., M. D. Heilman, R. J. P. Lyon, L. N. Namken, D. Simonetti, J. R. Thomas, C. L. Wiegand and J. T. Woolley. 1970. Soil water and plant relations. In: Remote Sensing with Special Reference to Agriculture and Forestry. NAS, Washington, D. C. pp. 253-297.

Sinclair, T. R., R. M. Hoffer, and M. M. Schrieber. 1971. Reflectance and internal structure of leaves from several crops during a growing season. Agron. J. 63:864-868.

Tucker, C. J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sensing of Environment. 8:127-150.

Tucker, C. J. 1980. A spectral method for determining the percentage of green herbage material in clipped samples. Remote Sensing of Environment 9:175-181.

Tucker, C. J., J. H. Elgin, Jr. and J. E. McMurtrey, III. 1979. Relationship of red and photographic infrared spectral radiances to alfalfa biomass, forage water content, percentage canopy cover and severity of drought stress. NASA Tech. Memo 80272. Goddard Space Flight Center, Greenbelt, Maryland.

Woolley, J. T. 1971. Reflectance and transmittance of light by leaves. Plant Physiol. 47:656-662.

APPENDIX I

ESTIMATION OF INCOMING LONGWAVE RADIATION

B. R. Gardner and B. L. Blad

Blad (1976) described a method by which incoming longwave radiation (B*) can be directly measured. The method consists of measuring the apparent temperature of an aluminum plate with an infrared thermometer (IRT) and its actual temperature with embedded thermocouples. The emissivity of the plate must be known. B* is calculated from the following expressions.

$$B^* = \frac{\sigma T_{IR}^4 - \varepsilon_p T_p^4}{1 - \varepsilon_p}$$

where σ is the Stephan-Boltzmann constant, ε_p is the emissivity of the aluminum plate, T_p is the observed infrared temperature (°K) and T_{IR} is the thermocouple temperature of the aluminum plate (°R).

Idso and Jackson (1969) studied the relationship between clear-sky B* and screen-level air temperature. They concluded that B* could be accurately estimated under clear-sky conditions using the following equation:

$$B^* = \sigma T^4 (1-0.261 \exp [-7.77 (10^{-4}) (273-T)^2])$$

where T is screen-level air temperature (°K).

The method described by Blad has the advantage of theoretical accuracy and is relatively simple to use. By comparison the method developed by Idso and Jackson is more simple to use. The two methods were compared at mid-day on 26 clear days throughout the 1978 growing season at the Sandhills Agricultural Laboratory (Fig. 1).

The results of the comparison indicate that the B* values obtained with measurements were generally higher than those calculated with the Idso-Jackson equation. This does not mean that the Idso-Jackson equation is invalid, however.

True canopy temperature is calculated from the following expression:

$$T_c = \frac{(\sigma T_{IR}^4 - (1 - \varepsilon_c)\, B^*)^{\frac{1}{4}}}{\varepsilon_c \sigma}$$

where ε_c is the emissivity of the crop and T_c is true canopy temperature (°K). Since ε_c for most vegetative surfaces is about 0.97, it is apparent that the effect of even fairly large B* values on corrected temperatures will be relatively small. Consequently, we computed the midday IRT temperature of well-watered corn for 63 days during the season. These days represent wide ranges of cloudy, partly-cloudy and clear skies (Fig. 2). Regression analysis indicates that canopy temperature estimates using B* values from either method differed by no more than 0.3 C for crop temperatures between 20 and 35 C.

We conclude that either method of estimating B* will yield sufficiently accurate B* values for calculating mid-day crop temperatures for operational purposes. For research purposes, however, we feel the theoretical accuracy of the measurement method is preferable.

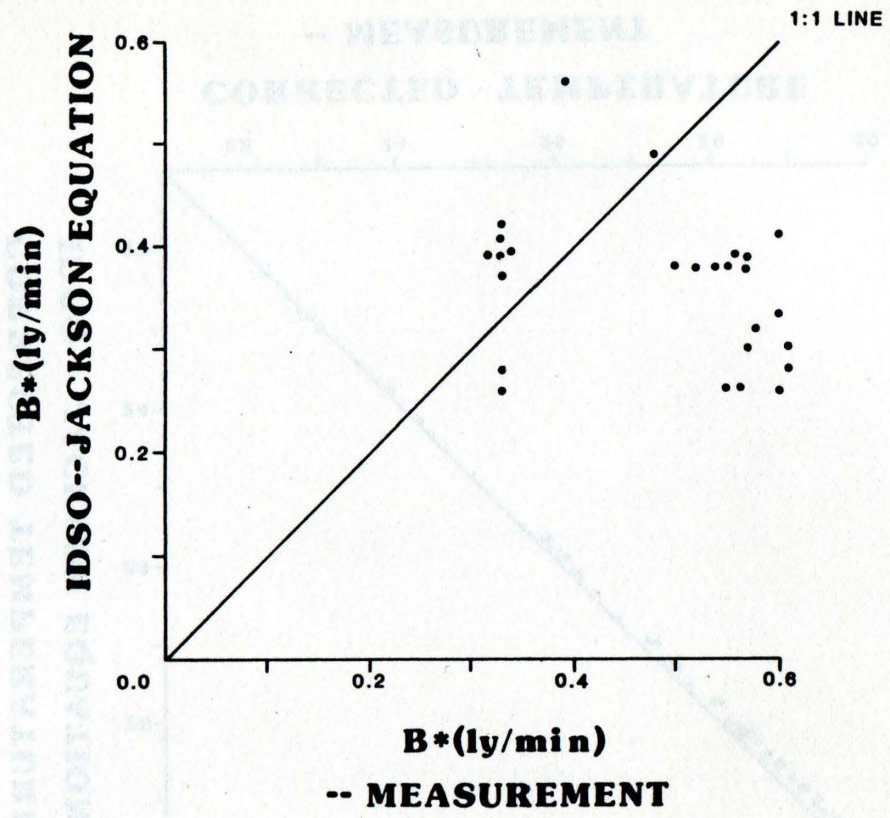


Fig. 1. Comparison between the Idso-Jackson (1969) equation for estimating incoming longwave radiation (B*) and a method for directly measuring B* (Blad, 1976).

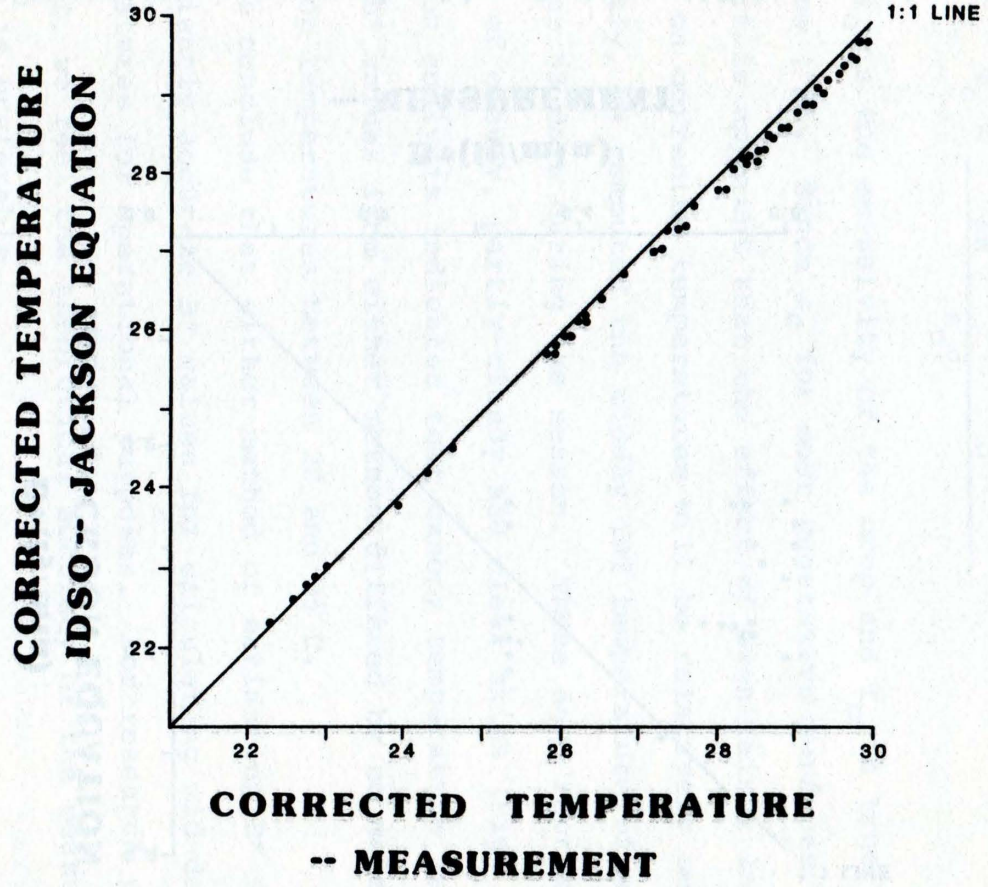


Fig. 2. Corrected mid-day infrared canopy temperature of well-irrigated corn, calculated using the Idso-Jackson equation (1969) and the direct measurement method (Blad, 1976).

REFERENCES

Blad, B. L. and N. J. Rosenberg. 1976. Measurement of crop temperature by leaf thermocouple, infrared thermometry and remotely sensed thermal imagery. Agron. J. 68:635-641.

Idso, S. B. and R. D. Jackson. 1969. Thermal radiation from the atmosphere. J. Geophys. Res. 74:5397-5403.

APPENDIX II

RELATIONSHIP BETWEEN LEAF TEMPERATURE AND NET RADIATION

B. R. Gardner and B. L. Blad

Although leaf temperatures are directly affected by the intensity of net radiation, they are not controlled entirely by radiation. This is evident in net radiation and leaf temperature measurements made at the Sandhills Agricultural Laboratory in well-irrigated corn on July 28, 1978, (Fig. 1). On this date, prior to solar noon, leaf temperatures increased with increasing net radiation. As net radiation decreased in the afternoon, leaf temperatures remained relatively high in response to the elevated air temperature. The dual dependence of leaf temperature on air temperature and net radiation illustrates the reason dynamic plant simulation models must be capable of responding to changes in both parameters.

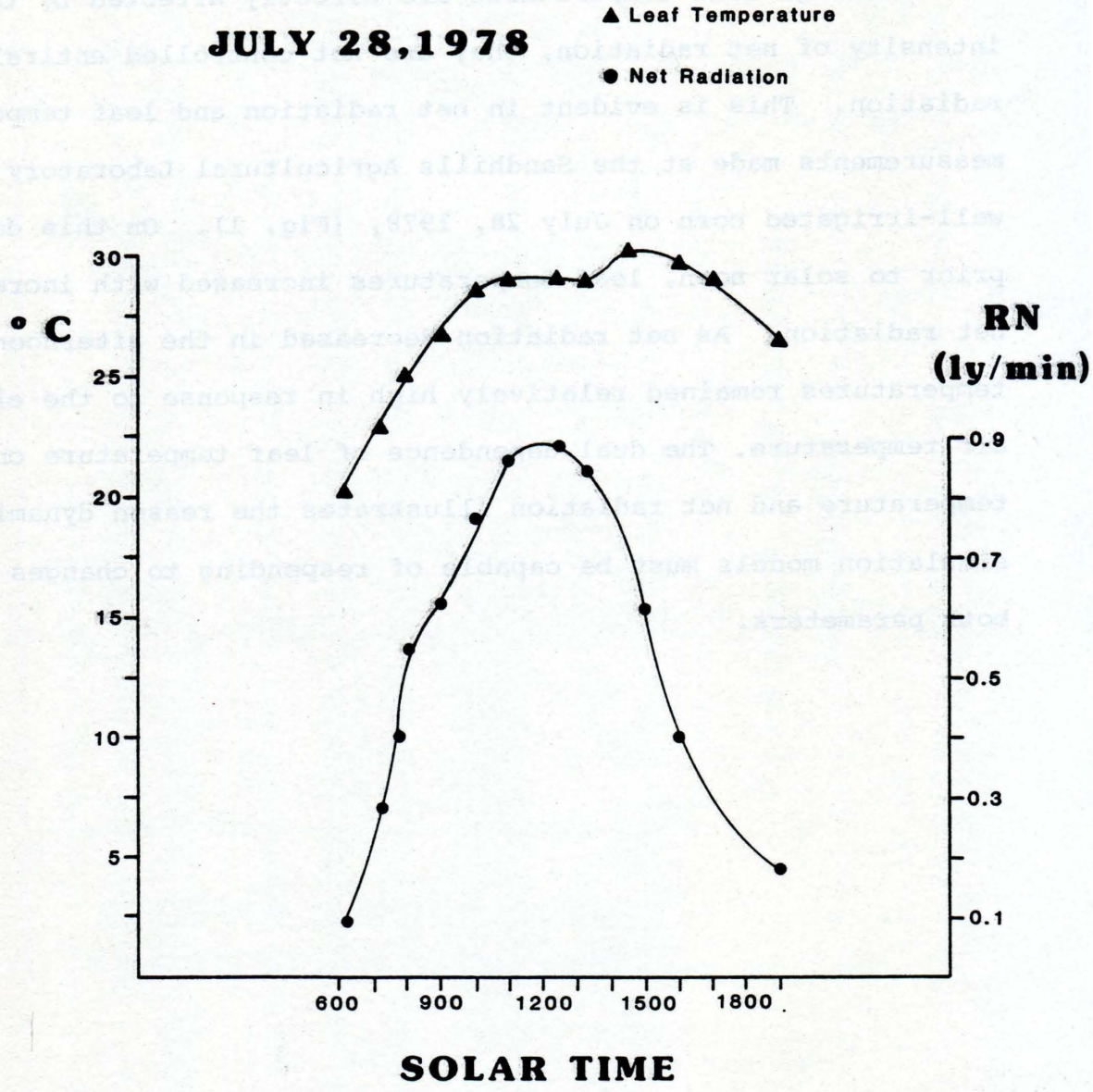


Fig. 1. Leaf thermocouple temperature of exposed leaves at the top of a well-irrigated corn canopy and net radiation above the same canopy on July 28, 1979.

APPENDIX III

EVALUATION OF AIR TEMPERATURE MEASUREMENTS MADE WITH THE TELATEMP AG 42 INFRARED THERMOMETER

B. R. Gardner and B. L. Blad

One of the features of the Telatemp Ag 42 Infrared Thermometer is its capacity to calculate the difference between crop temperature and ambient air temperature (ΔT) through the use of a small bead thermocouple. Ambient air temperature can then be calculated.

We tested the accuracy of the Ag 42 measurement by comparing the air temperature calculated from the Telatemp with air temperature measured with constantan-evanohum thermocouples at three meters above the soil surface in a corn canopy. This is the same height from which crop temperature and ΔT measurements were made. Data were collected at mid-day on 14 days in 1979. Results indicate that there is a strong tendency for the Telatemp to overestimate air temperature by 1 to 2 C. This overestimation is probably a function of windspeed. At lower windspeeds, ventilation will be inadequate, resulting in a biased temperature estimate with the Telatemp.

We feel that at moderate windspeeds the ΔT measured by the Ag 42 may be sufficiently accurate (1 to 2 C) for general estimates of air temperature. The accuracy needed for precise field research is not provided, however.

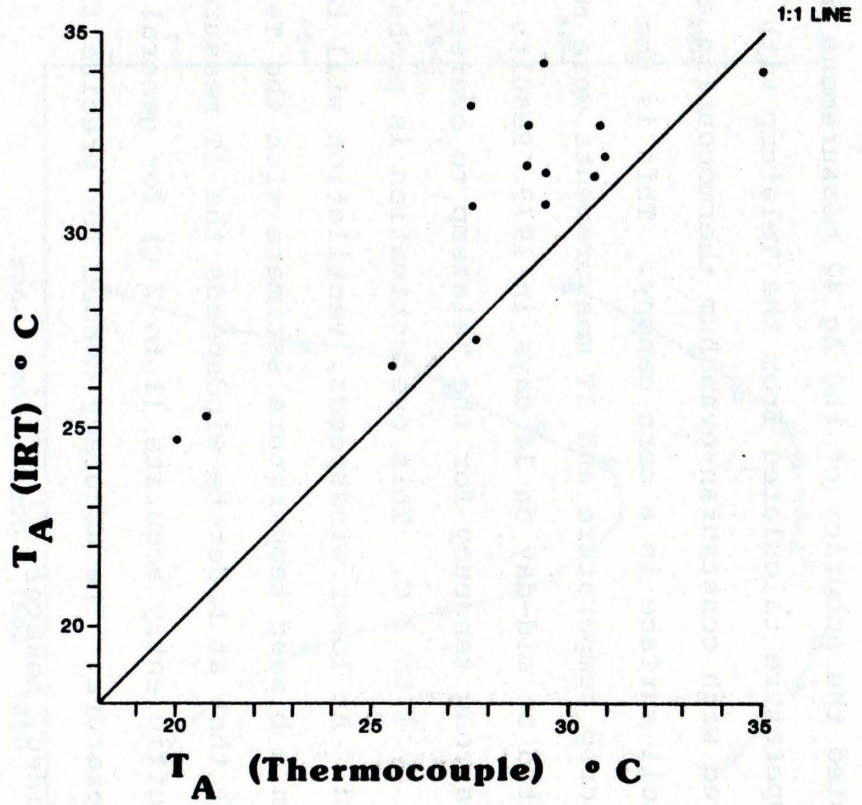


Fig. 1. Comparison between mid-day air temperature (TA) at three meters as with a radiation shielded thermocouple and with a small bead thermocouple on the Telatemp Ag 42 Infrared Thermometer.

APPENDIX IV

DISTINGUISHING CORN FROM ALFALFA USING MULTISPECTRAL DATA

B. R. Gardner, B. L. Blad and B. Kranz

Previous multispectral studies have shown that alfalfa is more reflective than corn in the near infrared region. This finding is confirmed in Fig. 1 of Appendix IV. Crop temperature studies have indicated that alfalfa tends to be several degrees cooler than corn due to its higher evapotranspiration capacity. We felt that it should be possible to construct a three-band composite image which unmistakably separates the two crops. One combination which achieves the desired effect is that of channels 1, 8 and 11, representing the visible, near infrared and thermal regions (Fig. 1).

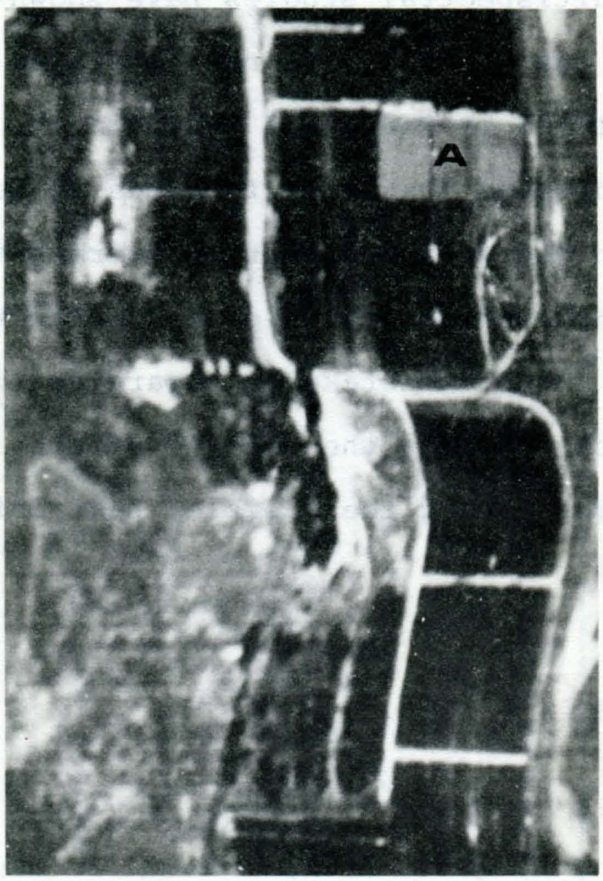


Fig. 1. Three channel color composite of the Sandhills Agricultural Laboratory for the August 30, 1979 data. Color assignments were Blue--Channel 11, Green--Channel 1, and Red--Channel 8. Alfalfa area is labeled A.

PHOTO APPENDIX

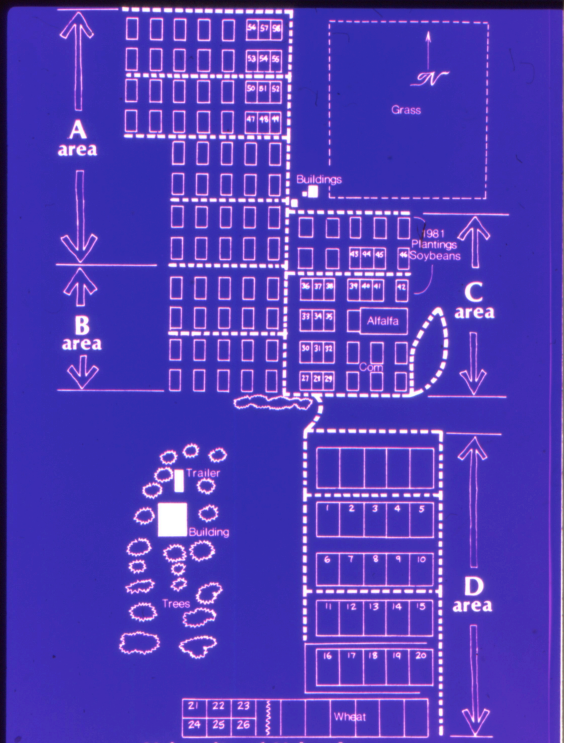
THE PHOTOS THAT FOLLOW WERE TAKEN AT THE SANDHILLS AGRICULTURAL LABORATORY BETWEEN 1978 AND 1984.

THE LABORATORY BUILDING AND THE SITE OF THE PLOTS ARE STILL VISIBLE ON GOOGLE MAPS:

https://www.google.com/maps/place/Cemetery+Rd,+Hall,+NE+69167/@41.627224,-100.8407819,327m/data=!3m1!1e3!4m5!3m4!1s0x8777c43f39dad1f9:0x8cafef49f0d83d2!8m2!3d41.6143034!4d-100.8571047

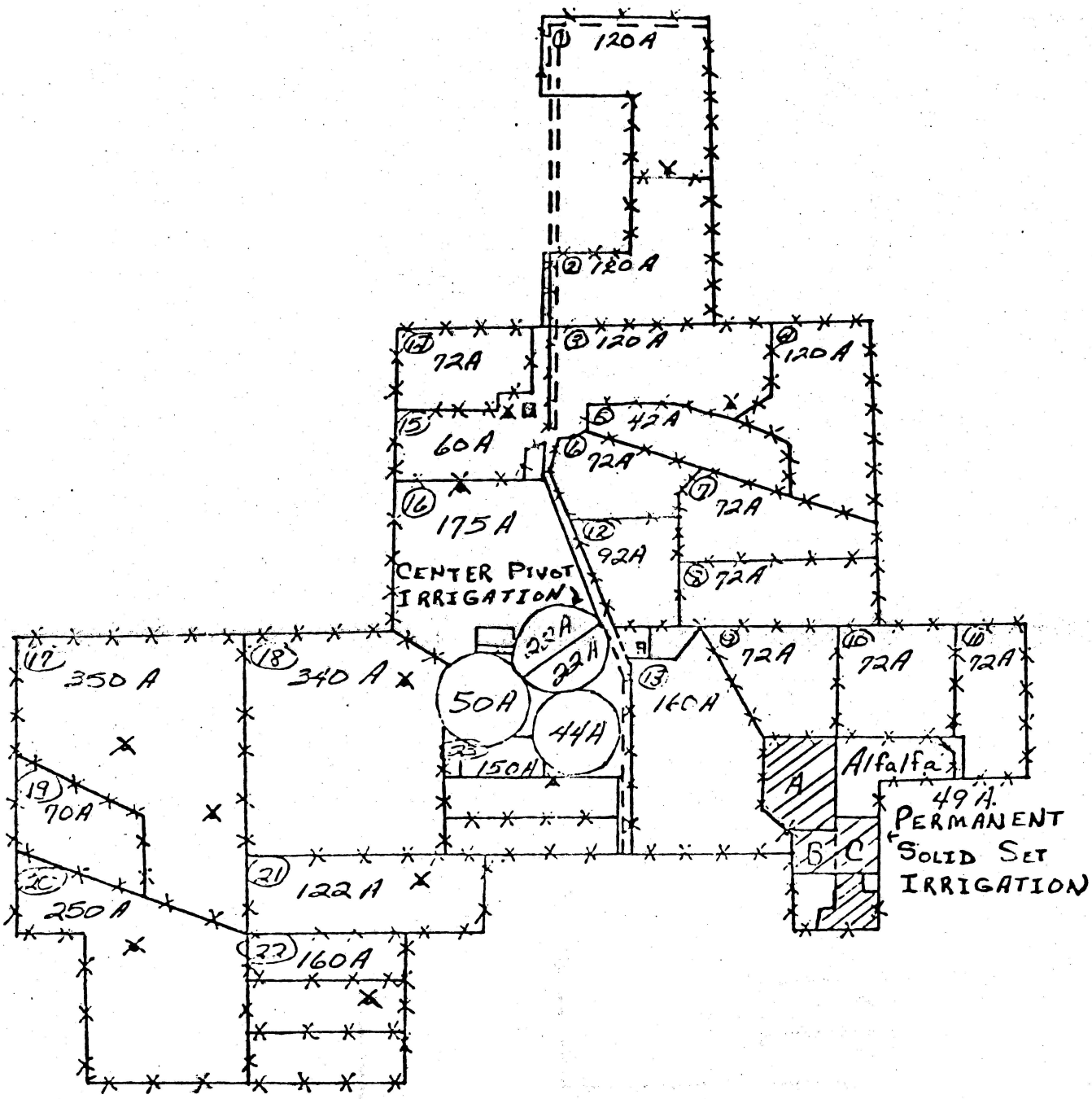
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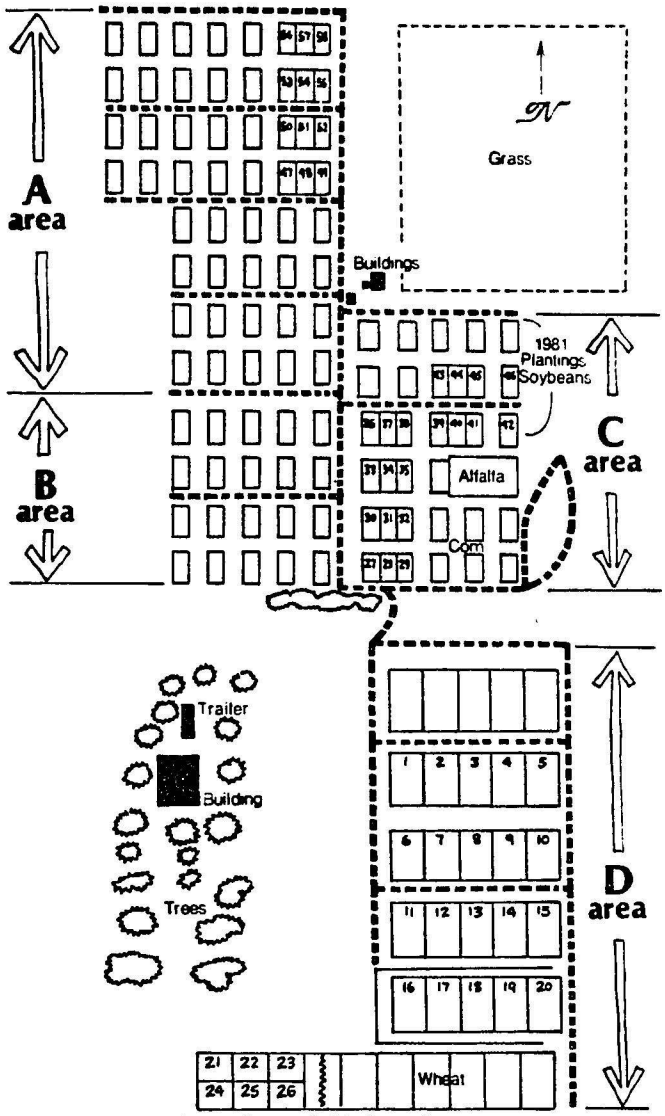
Note: These photos were not part of the original report, but have been added to this file for historical completeness. Many of the photos illustration material described in this report.


A area
B area
C area
D area
Grass
Buildings
1981 Plantings
Soybeans
Alfalfa
Corn
Trailer
Building
Trees
Wheat
University of Nebraska
Sandhills Ag. Lab. Solid Set Irrigation 1982

UNIVERSITY OF NEBRASKA

SANDHILLS AGRICULTURAL LABORATORY





Solid set irrigation area of the Sandhills Agricultural Laboratory showing plot locations

Latitude:41.626618 Longitude:-100.839648



1983 - Looking East .
B area (distance), C area (foreground)
A area (to the left). D area (behind the trees)

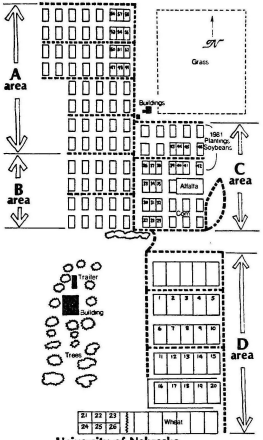




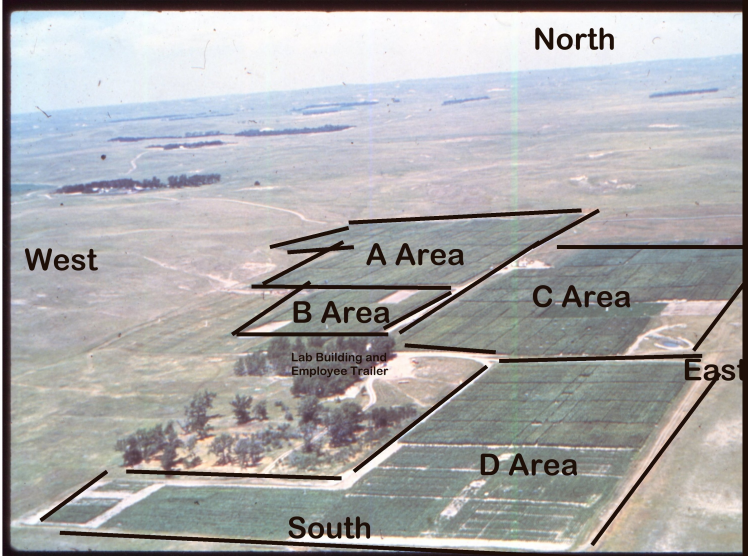
July 25, 1978 - The Sandhills Agricultural Lab, near North Platte. Photo taken by Bronson
This is where Bronson worked on his Masters and Ph.D. The work area, office and
female employee trailer were located in the clump of trees in the right center of the photo.



July 25, 1978 - The Sandhills Agricultural Lab, near North Platte. Photo taken by Bronson
This is where Bronson worked on his Masters and Ph.D. The work area, office and
female employee trailer were located in the clump of trees in the lower center of the photo.
The male housing was in the trees in the upper left of the photo.



Solid set irrigation area of the Sandhills Agricultural Laboratory showing plot locations



July 25, 1978 - The Sandhills Agricultural Lab, near North Platte. Photo taken by Bronson
This is where Bronson worked on his Masters and Ph.D. The work area, office and female employee trailer were located in the clump of trees in the lower center of the photo. The male housing was in the trees in the upper left of the photo.






Telatemp INFRARED THERMOMETER


EMISSIVITY
.9 9


EMISSIVITY
.99




STATE OF NEBRASKA
UNIVERSITY OF
NEBRASKA
239A



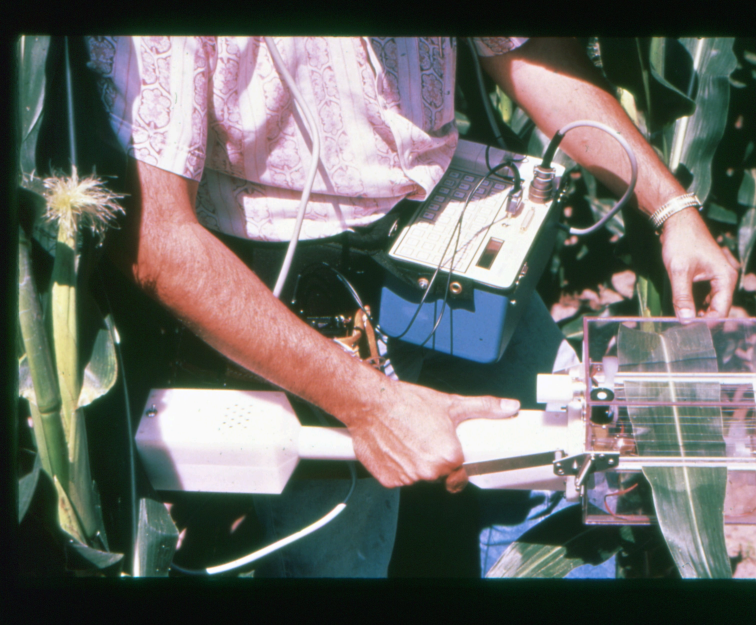




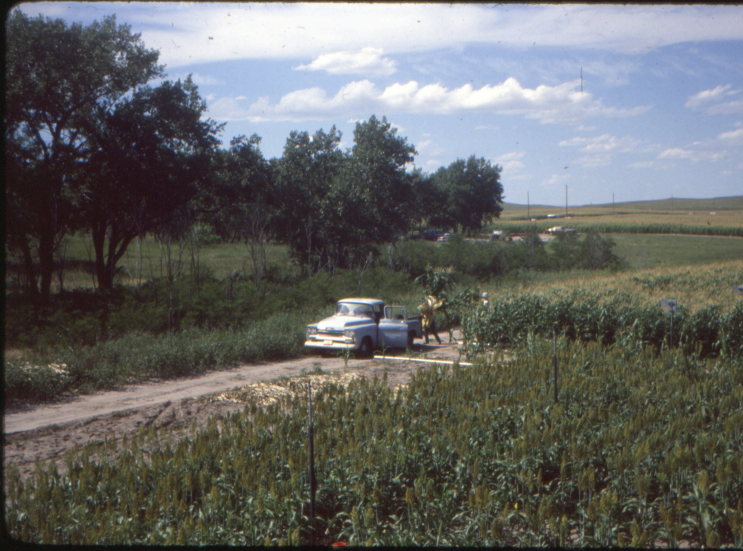




1978 August 22 Bronson's ladder, with the infrared thermometer on top.









1978 August 8. "D" area. Bronson's research plots
Note the gradient in height, caused by water stress.











July 19, 1978. Rob and John using the pressure bomb on corn.
Sandhills Agricultural Lab, Univ. of Nebraska, near North Platte.





June 13, 1978. Looking east from D area
Bronson's crop.
Sandhills Agricultural Lab, near North Platte, Nebraska



June 13, 1978. Looking north from the south part of D area.
Bronson's Research ladder is visible in the center of the photo.
Sandhills Agricultural Lab, near North Platte, Nebraska

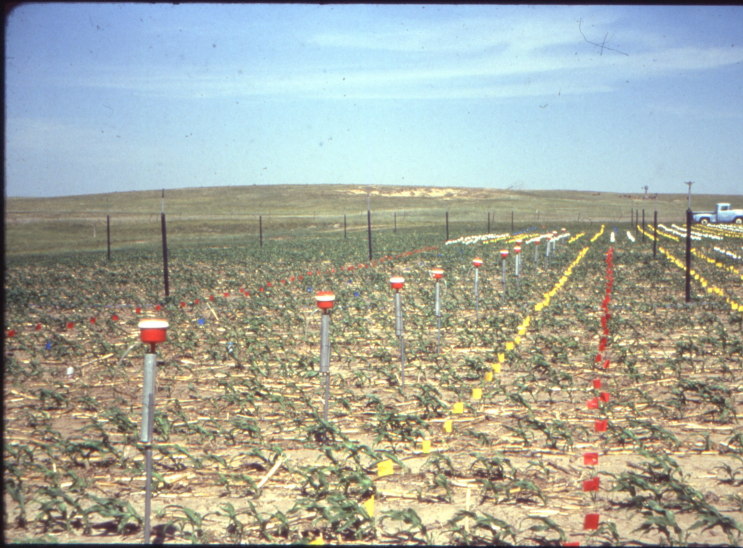


June 13, 1978. Looking north. The trees to the west of the southern part of D area.
Sandhills Agricultural Lab, near North Platte, Nebraska



June 13, 1978. Looking north. The road separating D area (on the right) and C area (straight ahead) is visible just behind the tractor. Sandhills Agricultural Lab, near North Platte, Nebraska





1978 June 13 .Plot 22, looking east
Sandhills Agricultural Lab, near North Platte, Nebraska



1978 June 13 .Plot 22, looking east
Sandhills Agricultural Lab, near North Platte, Nebraska



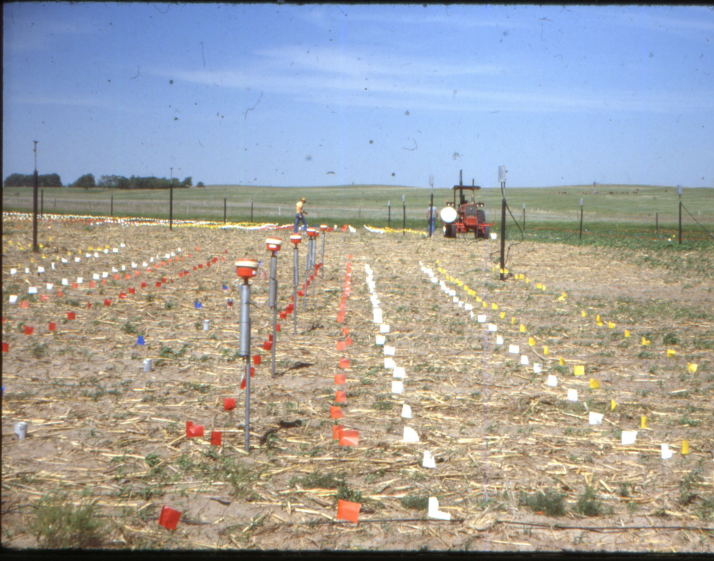
1978 June 13 .Plot 2N, looking south - Sorghum
Sandhills Agricultural Lab, near North Platte, Nebraska



1978 June 3 . Bronson's Research Ladder
Sandhills Agricultural Lab, near North Platte, Nebraska











1979 - Bronson taking infrared thermometer readings at the Sandhills Agricultural Lab, near North Platte (Univ of Nebraska)



1979 - Bronson taking infrared thermometer readings at the Sandhills Agricultural Lab, near North Platte (Univ of Nebraska)





1979 August 8. The weather station, looking south. The area with the trees is where our office building and employee trailer was located.



1979 August 8. The weather station, looking east.





1979 August 8. The irrigation pump, looking south. The trees in the distance are where our office and employee trailer was located.







1979 August 8. The "A" area windmill, looking west.





1979 August 8. Bronson making thermal measurements
"D" area. Sandhills Agricultural Laboratory, near North Platte.



1980 - Bronson analyzing the multi-spectral images that were taken on July 15, 1980 over the Sandhills Agricultural Laboratory

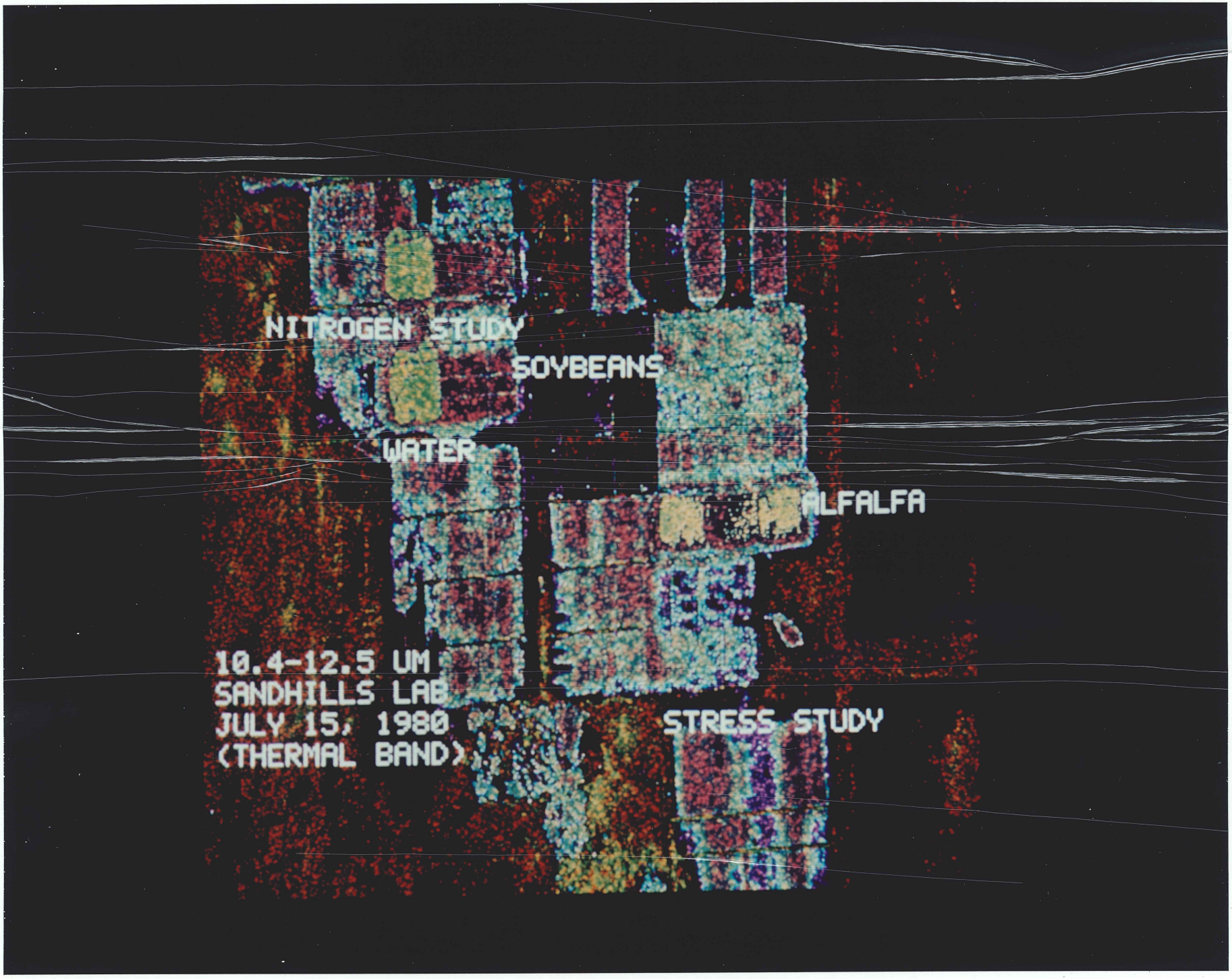


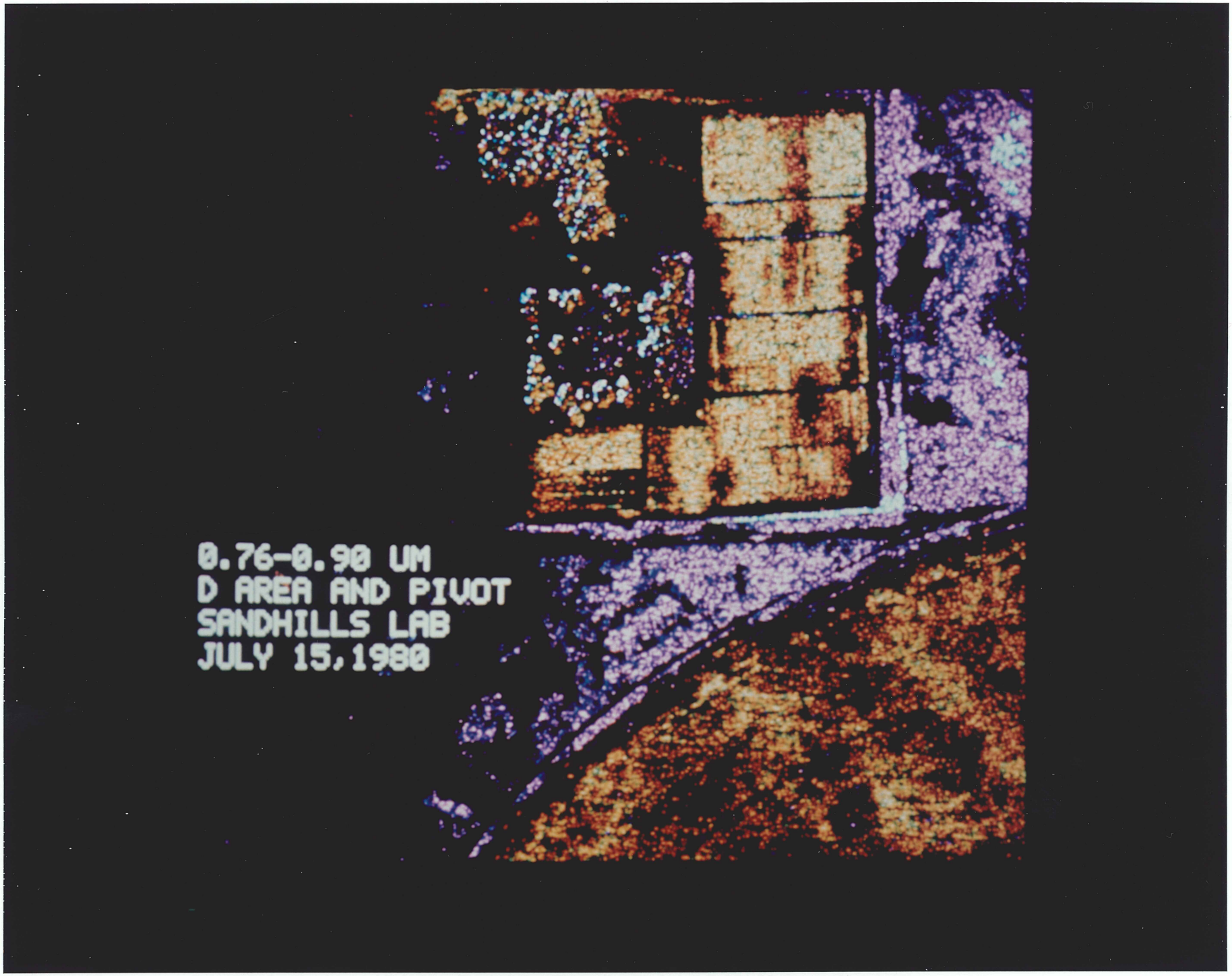
1980 - Blaine Blad analyzing the multi-spectral images that were taken on July 15, 1980 over the Sandhills Agricultural Laboratory



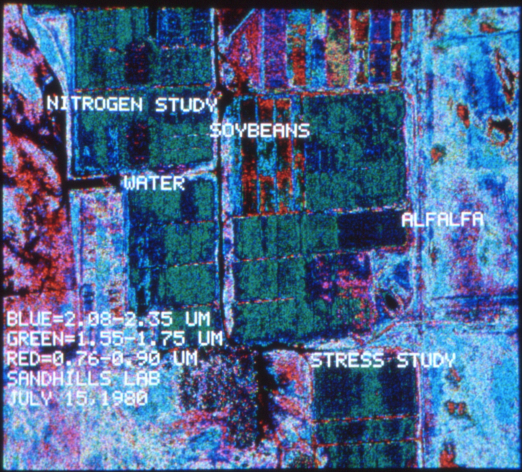
1980 - Ramana Rao analyzing the multi-spectral images that were taken on July 15, 1980 over the Sandhills Agricultural Laboratory



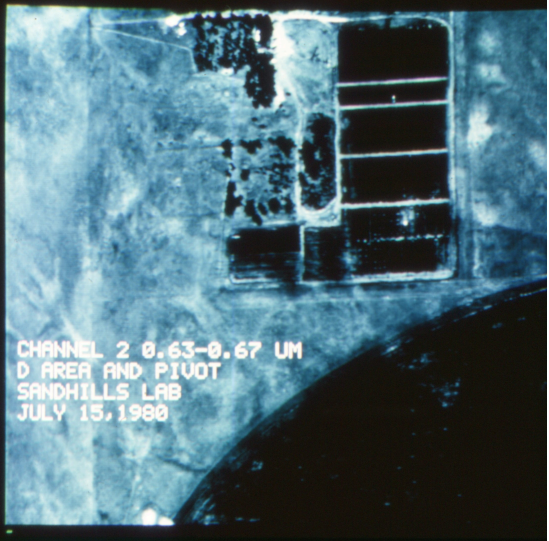

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
10.4-12.5 UM
SANDHILLS LAB
JULY 15, 1980
(THERMAL BAND)
STRESS STUDY


0.76-0.90 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980



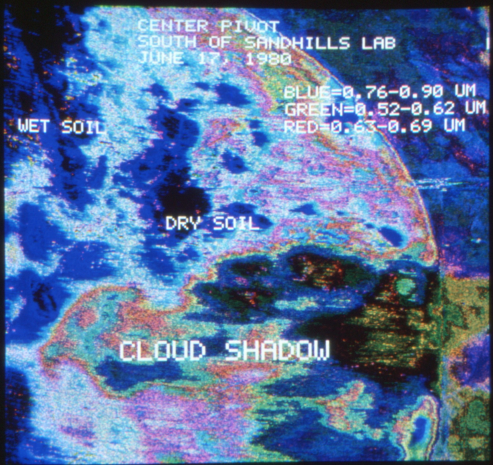


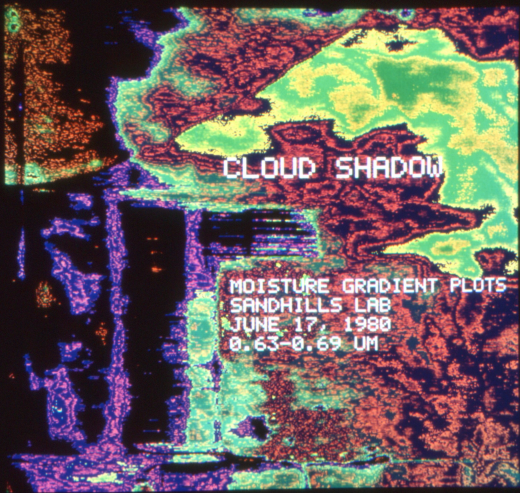
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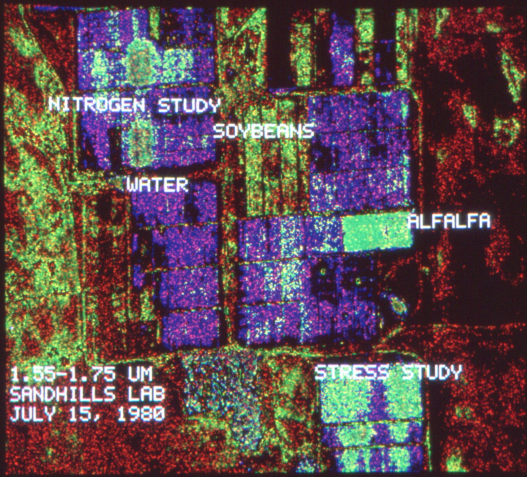

CHANNEL 2 0.63-0.67 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980

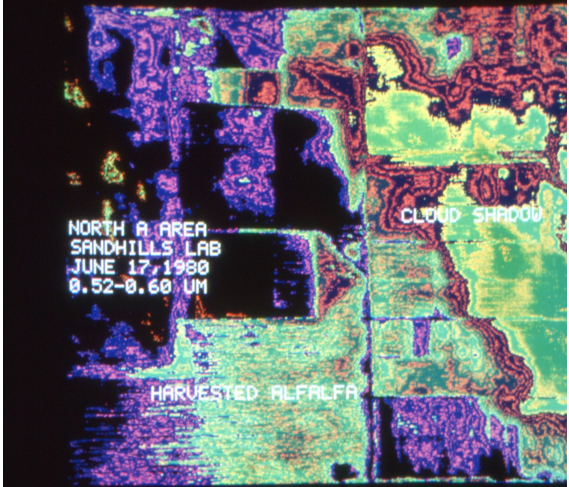


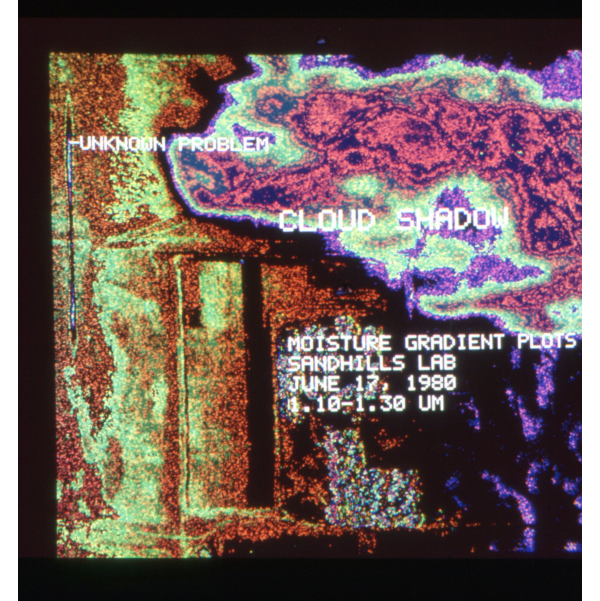
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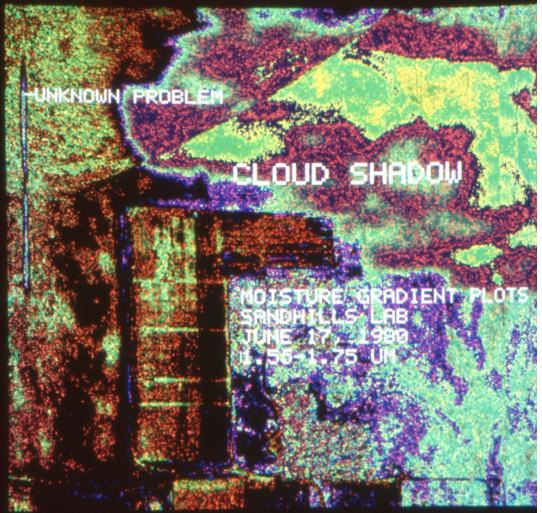

CENTER PIVOT
SOUTH OF SANDHILLS LAB
JUNE 17, 1980
BLUE=0.76-0.90 UM
GREEN=0.52-0.62 UM
RED=0.63-0.69 UM
WET SOIL
DRY SOIL
CLOUD SHADOW


CLOUD SHADOW
MOISTURE GRADIENT PLOTS
SANDHILLS LAB
JUNE 17, 1980
0.63-0.69 UM

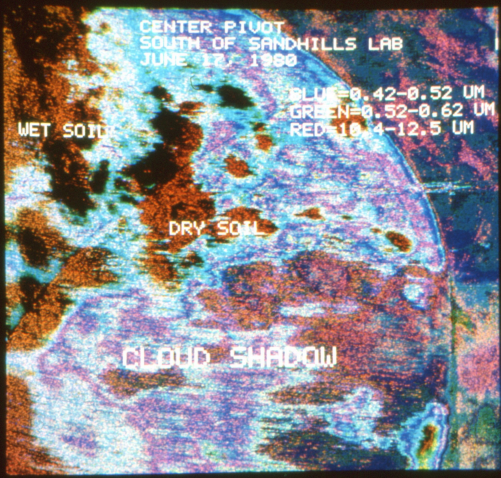

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
1.55-1.75 UM
SANDHILLS LAB
JULY 15, 1980
STRESS STUDY

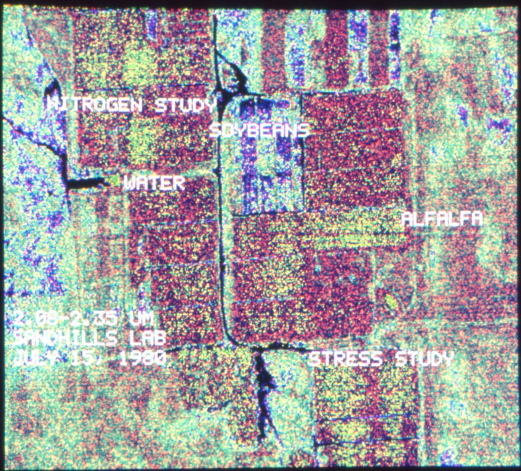

NORTH A AREA
SANDHILLS LAB
JUNE 17,1980
0.52-0.60 UM
CLOUD SHADOW
HARVESTED ALFALFA


UNKNOWN PROBLEM
CLOUD SHADOW
MOISTURE GRADIENT PLOTS
SANDHILLS LAB
JUNE 17, 1980
1.10-1.30 UM

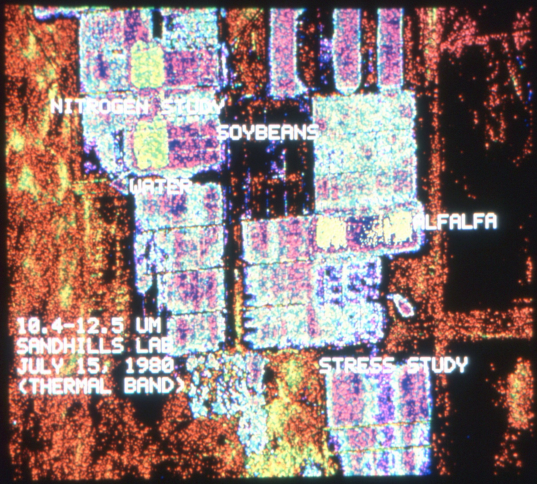

UNKNOWN PROBLEM
CLOUD SHADOW
MOISTURE GRADIENT PLOTS
SANDHILLS LAB
JUNE 17, 1980
1.50-1.75 UM

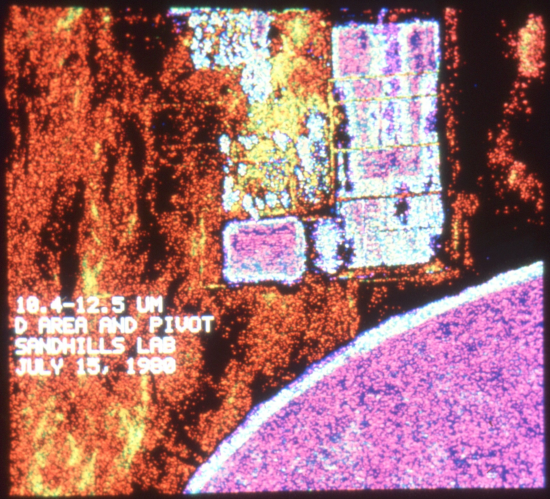

CENTER PIVOT
SOUTH OF SANDHILLS LAB
JUNE 17, 1980
1.10-1.30 UM
WET SOIL
DRY SOIL
CLOUD SHADOW

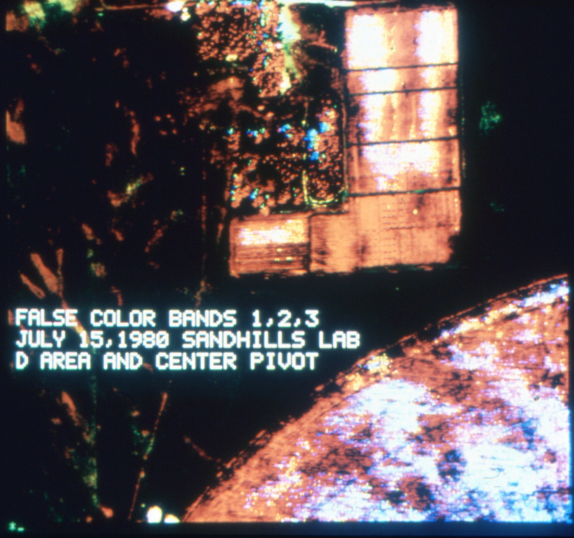

CENTER PIVOT
SOUTH OF SANDHILLS LAB
JUNE 12, 1980
BLUE=0.42-0.52 UM
GREEN=0.52-0.62 UM
RED=10.4-12.5 UM
WET SOIL
DRY SOIL
CLOUD SHADOW


NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
2:05:24:45 PM
SANDHILLS LAB
JULY 15, 1980
STRESS STUDY


NITROGEN STUDY
SOYBEANS
BLUE=0.52-0.60 UM
GREEN=0.63-0.69 UM
RED=0.76-0.90 UM
SANDHILLS LAB
JULY 15, 1980
ALFALFA
STRESS STUDY

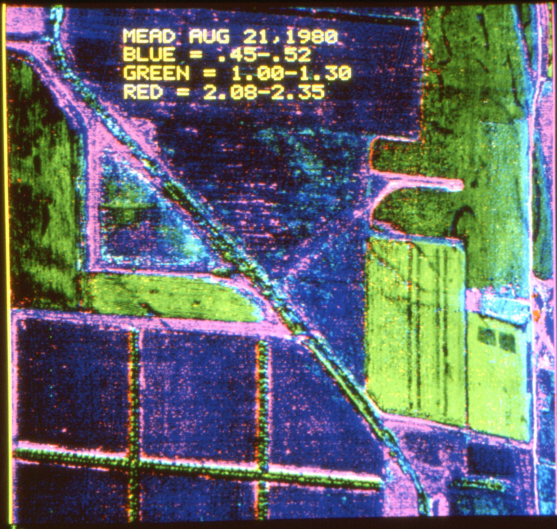

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
10.4-12.5 UM
SANDHILLS LAB
JULY 15, 1980
(THERMAL BAND)
STRESS STUDY

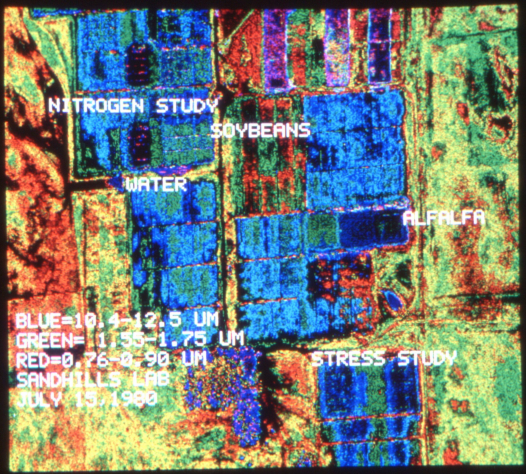

10.4-12.5 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15, 1980

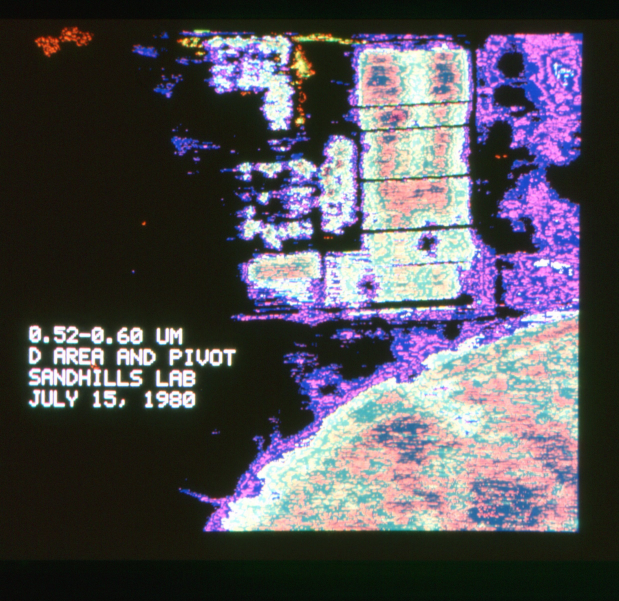

FALSE COLOR BANDS 1,2,3
JULY 15,1980 SANDHILLS LAB
D AREA AND CENTER PIVOT


NORTH END OF D AREA
SANDHILLS LAB
JUNE 17,1980
BLUE=0.45-0.52 UM
GREEN=1.52-1.73 UM
RED=10.4-12.5 UM
CLOUD SHADOW
HARVESTED ALFALFA
(NOTE HAY BALES)

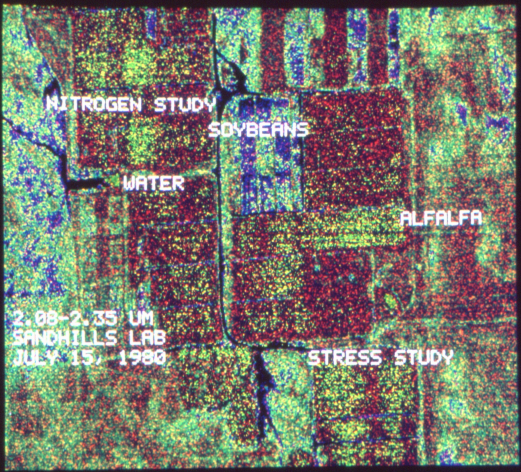

CLOUD SHADOW
NORTH A AREA
SANDHILLS LAB
JUNE 17,1980
BLUE= 2.08-2.35 UM
GREEN=10.4-12.5 UM
RED=1.55-1.75 UM
HARVESTED ALFALFA

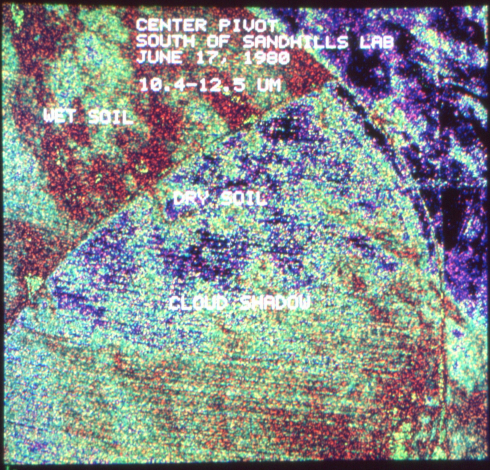

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GREEN = 1.00-1.30
RED = 2.08-2.35

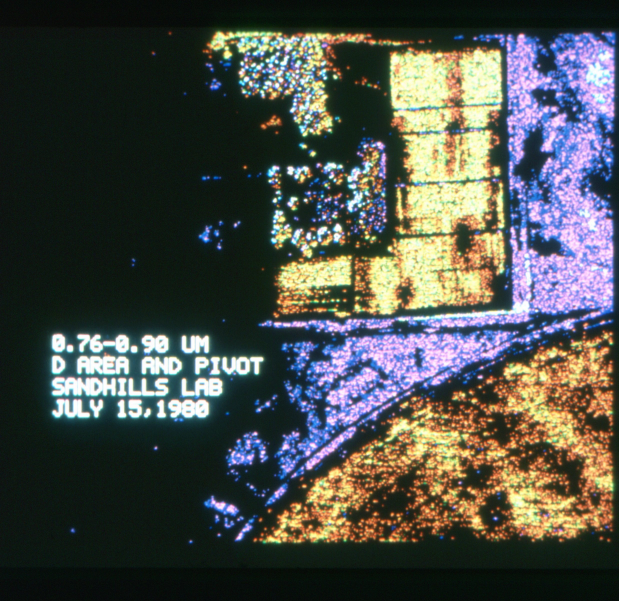

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
BLUE=10.4-12.5 UM
GREEN= 1.55-1.75 UM
RED=0.76-0.90 UM
STRESS STUDY
SANDHILLS LAB
JULY 15,1980

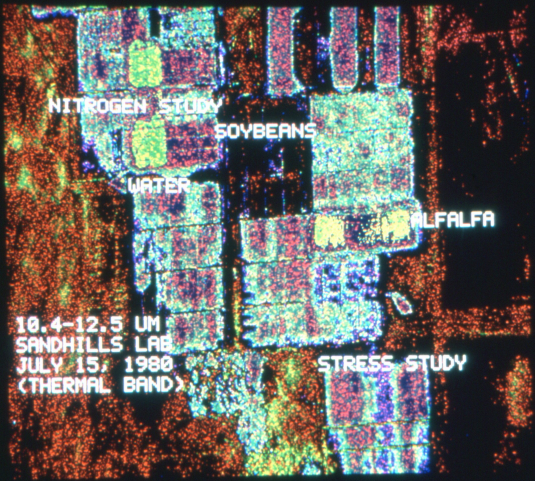

0.52-0.60 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15, 1980

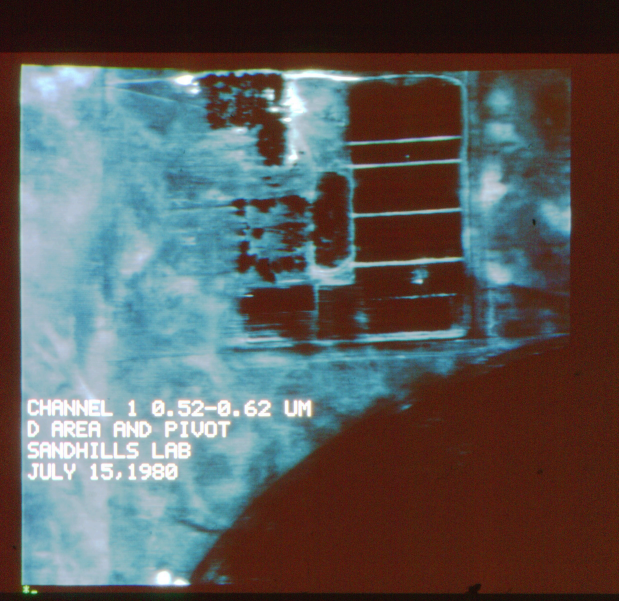

FALSE COLOR BANDS 1,2,3
JULY 15,1980 SANDHILLS LAB
D AREA AND CENTER PIVOT

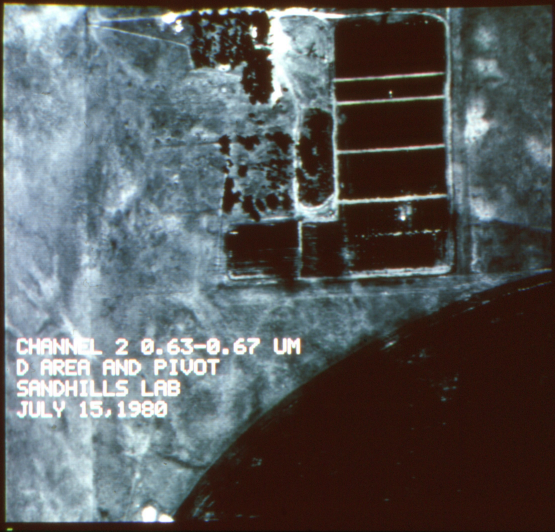

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
2.08-2.35 UM
SANDHILLS LAB
JULY 15, 1980
STRESS STUDY

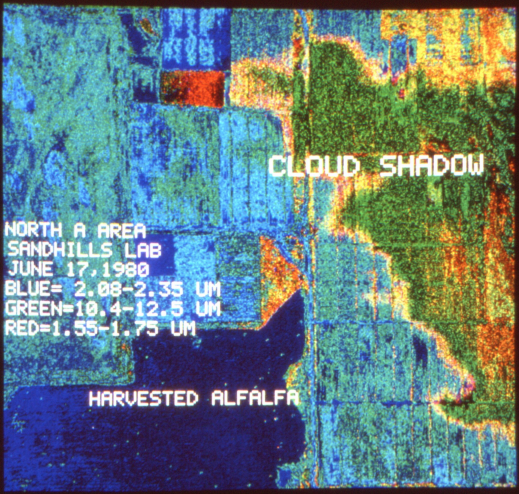

CENTER PIVOT
SOUTH OF SANDHILLS LAB
JUNE 17, 1980
10.4-12.5 UM
WET SOIL
DRY SOIL
CLOUD SHADOW

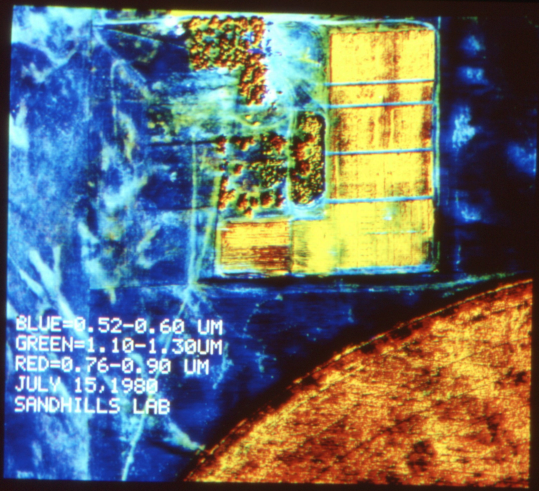

0.76-0.90 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980

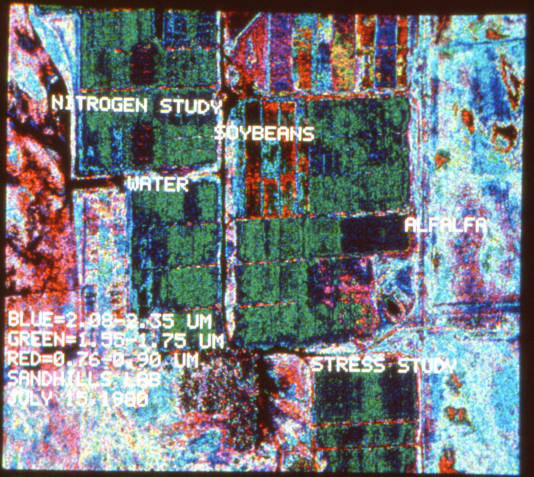

NITROGEN STUDY
SOYBEANS
WATER
ALFALFA
10.4-12.5 UM
SANDHILLS LAB
JULY 15, 1980
(THERMAL BAND)
STRESS STUDY


CHANNEL 1 0.52-0.62 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980

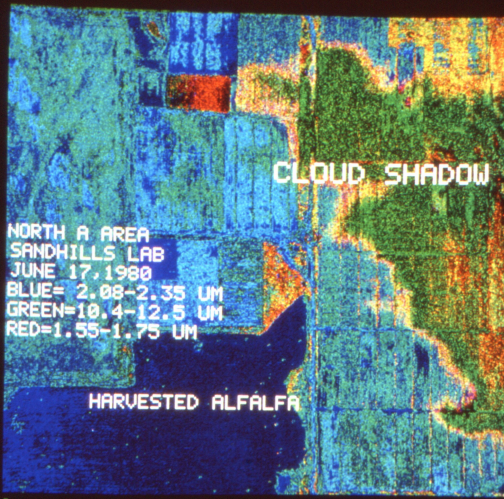

CHANNEL 2 0.63-0.67 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980

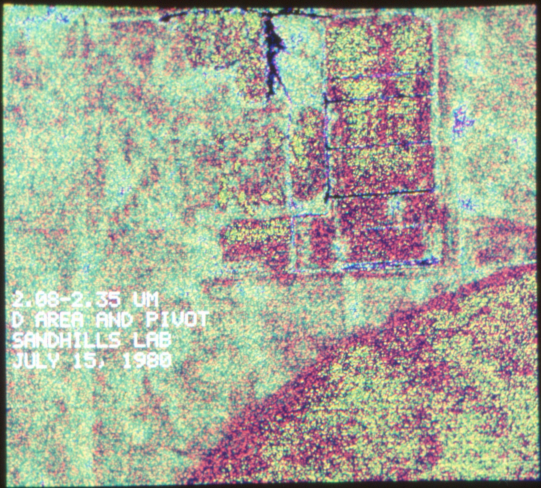

CLOUD SHADOW
NORTH A AREA
SANDHILLS LAB
JUNE 17,1980
BLUE= 2.08-2.35 UM
GREEN=10.4-12.5 UM
RED=1.55-1.75 UM
HARVESTED ALFALFA

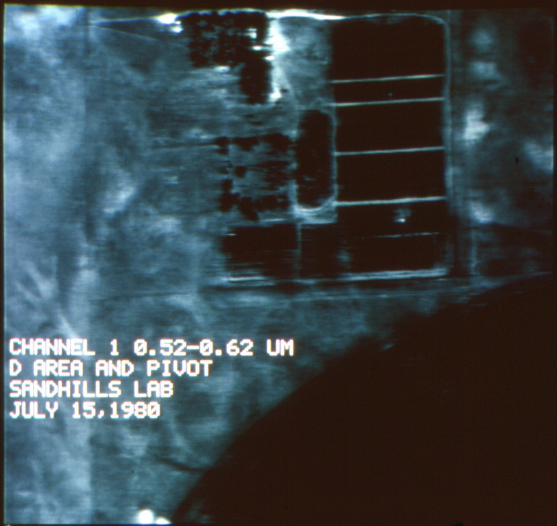

BLUE=0.52-0.60 UM
GREEN=1.10-1.30UM
RED=0.76-0.90 UM
JULY 15,1980
SANDHILLS LAB

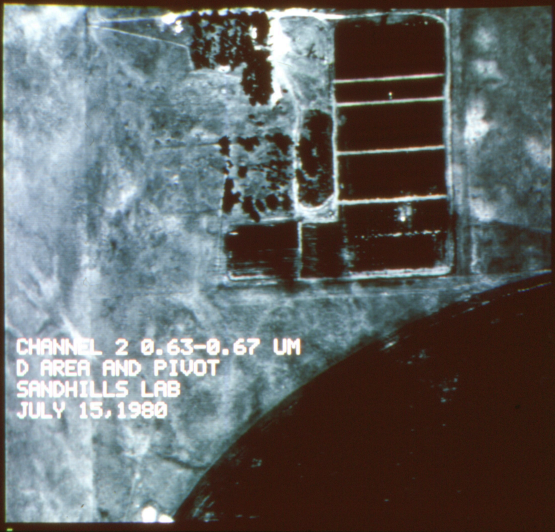


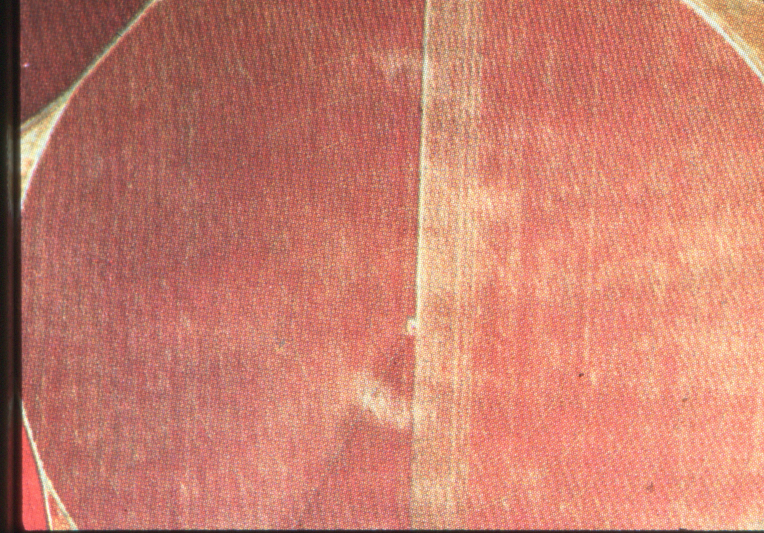
*GRAPHIC_1_* LABEL BY FACTOR 2


CLOUD SHADOW
NORTH A AREA
SANDHILLS LAB
JUNE 17,1980
BLUE= 2.08-2.35 UM
GREEN=10.4-12.5 UM
RED=1.55-1.75 UM
HARVESTED ALFALFA


2.08-2.35 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15, 1980


CHANNEL 1 0.52-0.62 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980


CHANNEL 2 0.63-0.67 UM
D AREA AND PIVOT
SANDHILLS LAB
JULY 15,1980









June 1981 - Preparing the instruments



Polycorders used for electronically recording data

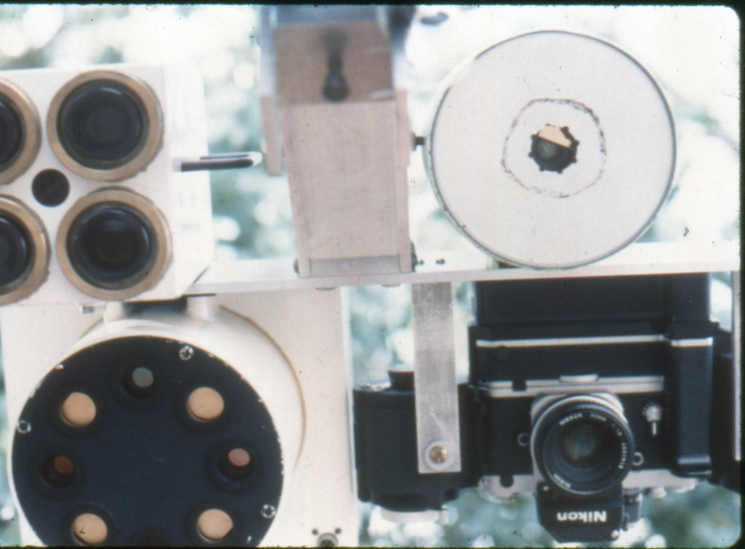


June 1981 - Bronson at the Sand Hills Agricultural Lab



June 1981 - Blaine Blad - Bronson's Ph.D. advisor, Univ. of Nebraska

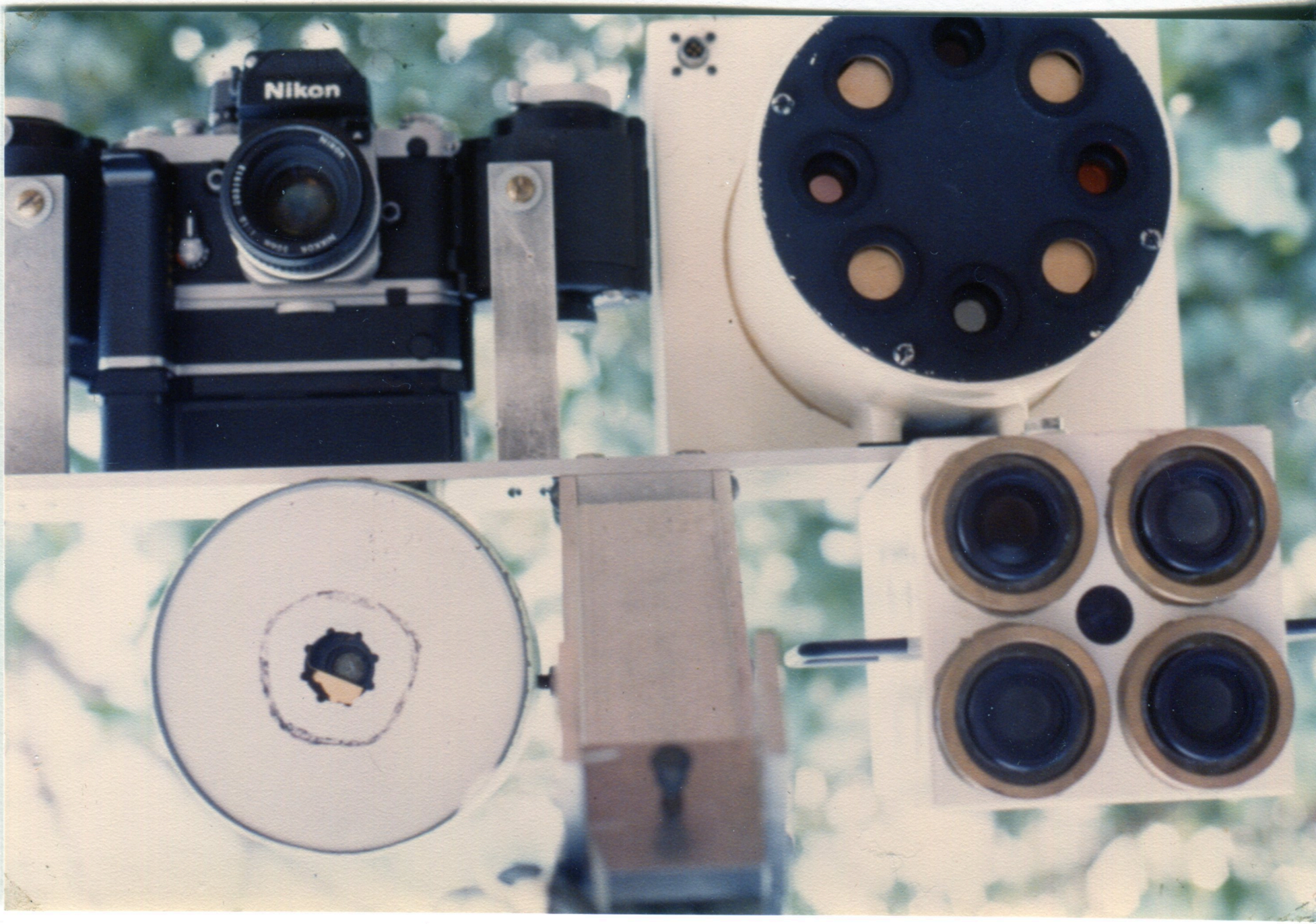
Bronson's Satellite Simulation equipment
4 channel, 8 channel, Infrared thermoment, 35 mm Nikon camera



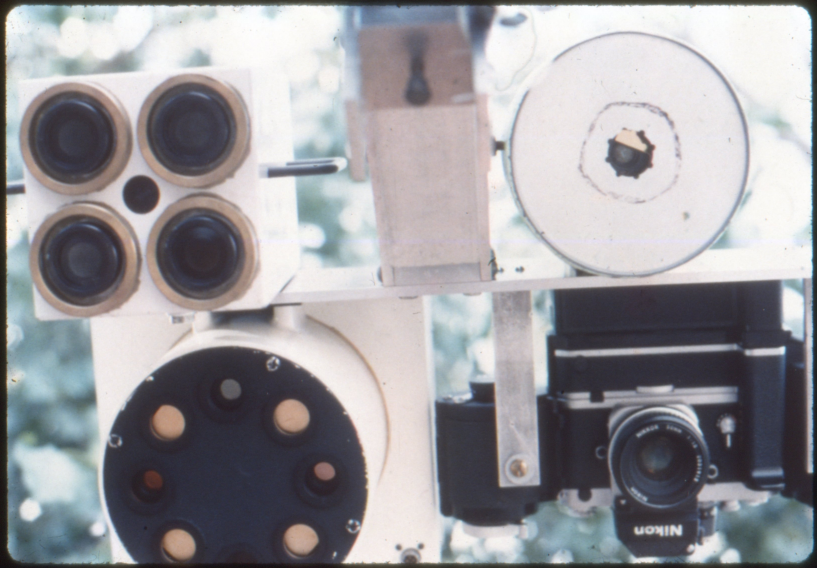



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omnidata
POLYCORDER
ENTER
PURDUE UNIVERSITY
OMNIDATA
ENTER


Nikon

Bronson's Satellite Simulation equipment
4 channel, 8 channel, Infrared thermoment, 35 mm Nikon camera





Adjusting the instruments


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433 CH



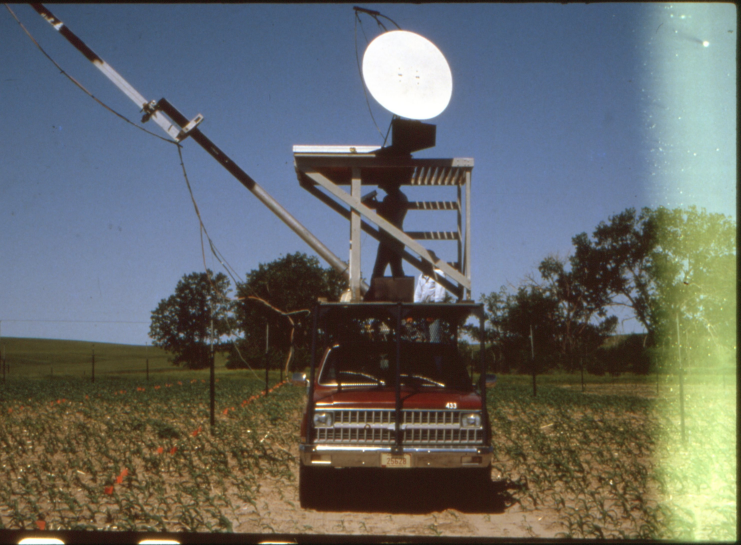
1983 Bronson Gardner, (bald on top) preparing for calibration
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1981 - June Bronson operating the instrument boom.



1981 - June Bronson operating the instrument boom.



1981 Bronson taking research data
Sandhilll Agricultural Laboratory, near North Platte, Nebraska





Bronson's Ph.D. research project. Blaine Blad on top of the truck.
Bronson is driving.



August 1981 - Bronson's research truck. Blaine Blad on top, using an infrared thermometer. Bronson, driving the truck and controlling the data recorder.





August 1981 - Campbell Weather Station -"D" Area
Sandhills Agricultural Lab, near Tryon Nebraska



August 1982. Field Lab building is on the right. Temporary work trailer on the left. Sandhills Ag Lab, near North Platte.



August 1982. Field Lab building is on the right. Temporary work trailer on the left. Sandhills Ag Lab, near North Platte.





June 10, Mike -- a high school math teacher
The Sandhills Laboratory building is in the background.


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June 10, 1980 Taking spectral measurements - Blaine Blad is on top, making adjustments
Sandhills Agricultural Lab - Bronson's "D" area. - Cindy Hays is driving



June 10, 1980 Howard Bryant - Taking measurements
Sandhills Agricultural Lab - Bronson's "D" area.



June 1981 - Bronson at the controls of the boom on the truck.



June 10, 1980 Bronson is starting to put instruments on the boom truck
The Sandhills Laboratory building is in the background.





A, B, and C areas as seen, looking east. The tractor shed is in the left, middle of the photo.
Sandhills Agricultural Laboratory



Sept. 1982. Taking measurements. Ramana Rao operating the boom.
Sandhills Agricultural Laboratory, near North Platte.



1982. The Lab building. and Cindy Hay's dog, Roamer. The employee trailer is to the right. Sandhills Agricultural Laboratory, near North Platte.



1982. The Lab building. and Cindy Hay's dog, Roamer
Sandhills Agricultural Laboratory, near North Platte.



August 1982. Taking readings in "D" area.
Sandhills Agricultural Laboratory, near North Platte.
Blaine Blad on top, using the infrared thermometer

1982. Ramana Rao, with the research instruments. Employee Trailer in the background
Sandhills Agricultural Laboratory, near North Platte.





1982. 1982. Ramana Rao, seated, Blaine Blad (on car hood), the Lab Building and the EmployeeTrailer Sandhills Agricultural Laboratory, near North Platte.



1982. Looking west from "D" area.
Sandhills Agricultural Laboratory, near North Platte.



1982. Looking south from "D" area.
Sandhills Agricultural Laboratory, near North Platte.



1982. The work trailer, to the south of the Lab Building
Sandhills Agricultural Laboratory, near North Platte.







August 1982. Taking readings in "D" area.
Sandhills Agricultural Laboratory, near North Platte.
Blaine Blad on top, using the infrared thermometer



1982. August. Bronson's research boom truck. Looking from the west side of "D" area to the east. Sandhills Agricultural Laboratory, near North Platte.



1982. August 8.The main irrigation pump
Sandhills Agricultural Laboratory, near North Platte.



1982. Looking south from the Lab building. One of the research trailers is on the right.
Sandhills Agricultural Laboratory, near North Platte.



1982. Kirk Clawson - Pressure Bomb readings
Sandhills Agricultural Laboratory, near North Platte.



1982."D" area, looking south
Sandhills Agricultural Laboratory, near North Platte.



1982. Looking east at "D" area.
Sandhills Agricultural Laboratory, near North Platte.



1982. Looking east at "D" area, from the Lab building
Sandhills Agricultural Laboratory, near North Platte.



1982. Looking north-east at "C" area.
Sandhills Agricultural Laboratory, near North Platte.



August 8, 1982. Blaine Blad - calibration the instruments using the barium sulfate calibration plate. Sandhills Agricultural Station, near North Platte



August 8, 1982. Blaine Blad - removing the lid from the barium sulfate calibration plate. Sandhills Agricultural Station, near North Platte











1982. August 8. "D" area "Dogleg" (the southern most part of "D" area.)
Sandhills Agricultural Laboratory, near North Platte.



1982. August 8. Looking north at "C" area.
Sandhills Agricultural Laboratory, near North Platte.







July 28, 1982 Bronson's Research Truck.
Sandhills Agricultural Laboratory University of Nebraska, near North Platte
Sattelite simulation: 8 channel, 4 channel, infrared thermomenter, 35 mm camera



July 28, 1982 Craig Daly (left) and Kirk Clawson



July 28, 1982 Cindy Hays (left), Ramana Rao, Blaine Blad
Sandhills Agricultural Station, near North Platte



July 28, 1982 Cindy Hays (left) and Ramana Rao
Sandhills Agricultural Station, near North Platte

July 28, 1982 Bronson, installing the sensor equipment





July 28, 1982 Blaine Blad (left) and Ramana Rao - making adjustments



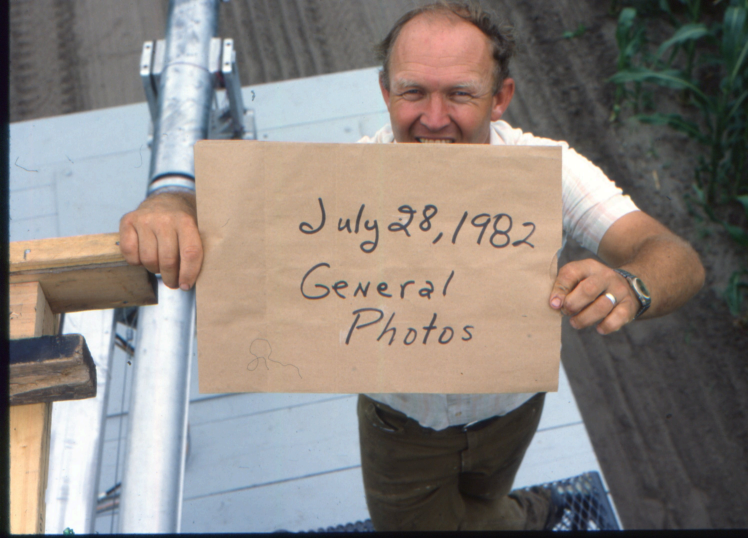
July 28, 1982 Bronson's Research Truck.
Sandhills Agricultural Laboratory University of Nebraska, near North Platte

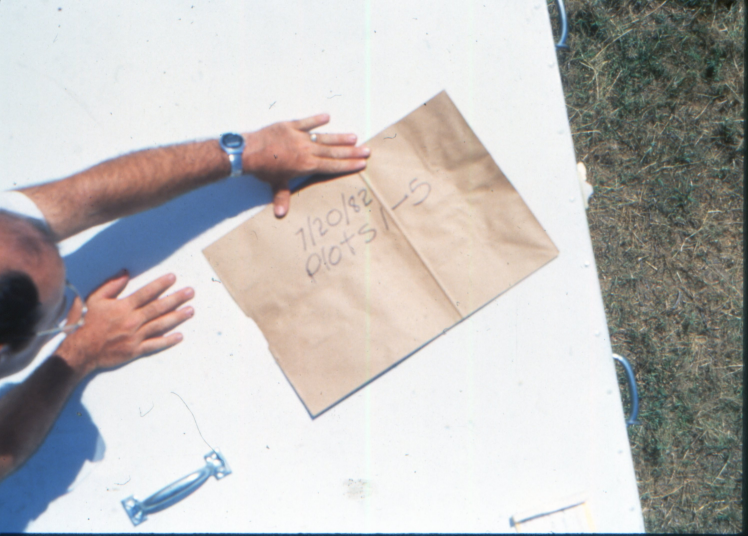









July 28, 1982
General
Photos


7/20/82
Plots 1-5



July 1982 Kirk Clawson (left) and Ramana Rao
Attaching the instruments to the boom truck.



July 1982 Kirk Clawson taking leaf measurements
Blain Blad (blue hat) and MIke, the math teacher
Sandhills Agricultural Lab, near North Platte



July 14, 1982. Kirk Clawson kneeling, Blad Blad on right. Other unknown



July 14, 1982 Kirk Clawson taking leaf measurements.



July 24, 1982 Blaine Blad. Sandhills Agricultural Laboratory
University of Nebraska, near North Platte




ALM





July 14, 1982. Blaine Blad kneeling





July 14, 1982 Blaine Blad taking leaf measurements.





1982. The "three wheeler" and the employee trailer
Sandhills Agricultural Laboratory, near North Platte.



1982. The Research Trailer. "C" area, looking south-east.
"Leaf Area Index" measurements were made here.
Sandhills Agricultural Laboratory, near North Platte.



July 1982 Technicians cleaning pipes used for neutron probe readings. Sandhills Agricultural Laboratory. The Lab Field Office is in the background.



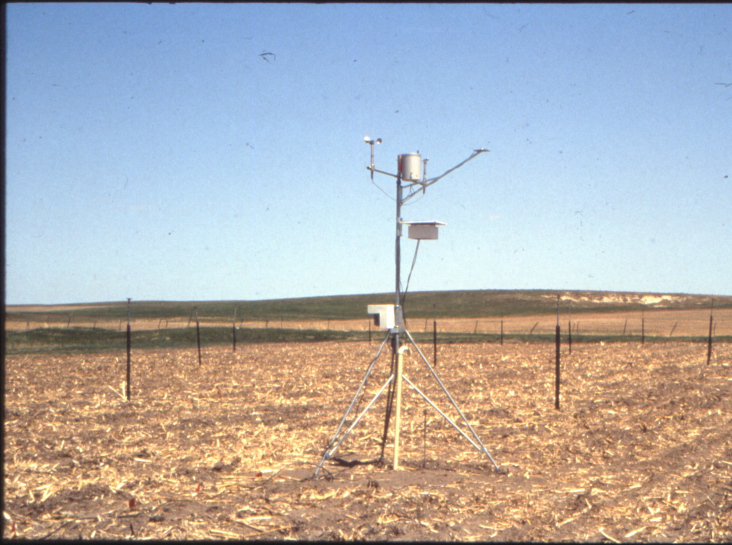
June 1982. "D" area, looking west - late afternoon
Sandhills Agricultural Laboratory, near North Platte



1982. Ed Schwartz, cleaning the discs, in front of the Lab building
Sandhills Agricultural Laboratory, near North Platte.



May 28, 1982 Campbell Weather Station
The tractor shed is in the background
Sandhills Agricultural Laboratory, near North Platte



May 28, 1982 Campbell Weather Station, looking east from "C" area.
Sandhills Agricultural Laboratory, near North Platte



Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
He worked during the summer of 1983, assisting his brother, Bronson with his Ph.D. project.
These are two of his co-workers.



Wayne Gardner's co-workers at the University of Nebraska's Sandhills Ag. Lab. Wayne worked there the summer of 1983, assisting his brother, Bronsonwith his Ph.D. project.



1983 Wayne Gardner and Craig Daly
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 Wayne Gardner
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



Wayne Gardner at the University of Nebraska's Sandhills Ag. Lab. He worked there the summer of 1983 assisting his brother, Bronson with his Ph.D. research project.



1983 Wayne Gardner and Craig Daly
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 Wayne Gardner
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
He worked during the summer of 1983, assisting his brother, Bronson with his Ph.D. project.



1983 Wayne Gardner (with Craig Daly's arms)
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
He worked during the summer of 1983, assisting his brother, Bronson with his Ph.D. project.



1983 Wayne Gardner
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 Ed Schwarz, Craig Daly, Wayne Gardner
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
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Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
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1983 Wayne Gardner, Craig Daly
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



Wayne Gardner at the University of Nebraska's Sandhills Ag. Lab. He worked there the summer of 1983 assisting his brother, Bronson with his Ph.D. research project.



Wayne Gardner at the Univ of Nebraska's Sandhills Ag Lab, near North Platte.
He worked during the summer of 1983, assisting his brother, Bronson with his Ph.D. project.


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CHRISTINE E GARDNER
102 BIRCH ST
VACAVILLE CA 95688
448-5987







Wayne Gardner at the University of Nebraska's Sandhills Ag. Lab. He worked there the summer of 1983, assisting his brother, Bronson with his Ph.D. project.



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
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1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983 September Wayne Gardner and Betty Walter, recording instrument readings.
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



1983. One of our research trailers. This was south of the lab building next to "C" area. Sandhills Agricultural Laboratory, near North Platte.



1983. "D" area, looking east.
Sandhills Agricultural Laboratory, near North Platte.



1983. "C" area, looking east. Note the weather station.
Sandhills Agricultural Laboratory, near North Platte.



1983 Bronson Gardner, (bald on top) preparing for calibration
Sandhilll Agricultural Laboratory, near North Platte, Nebraska



One of Bronson's Ph.D. research photos. Taken from the truck camera.
(very young corn)



One of Bronson's Ph.D. research photos. Taken from the truck camera.
(very young corn)



One of Bronson's Ph.D. research photos. Taken from the truck camera.
(very young corn)



Bronson's Ph.D. research project. Blaine Blad on top of the truck.
Bronson is driving.



July 11-13. Melvin Keener (Bronson's new boss at SOHIO) taking infrared thermometer readings at the Sandhills Agricultural Lab near North Platte, Nebraska for a research project initiated by Bronson for SOHIO (eventually, SOHIO became part of British Petroleum)



July 11-13.Bronson, getting ready to take takeinfrared thermometer readings at the Sandhills Agricultural Lab near North Platte, Nebraska for a research project initiated by Bronson for SOHIO (eventually, SOHIO became part of British Petroleum)



1984 - Thunderbolt Farm - Tornado damage to center pivot.

July - O'Neil Nebraska



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential, for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential,
for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential,
for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).



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HORIZON
SEEDS


HORIZON
SEEDS



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential,
for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential,
for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).



July 1984 - Bronson at the Sandhills Ag Lab, measuring leaf water potential,
for a research project initiated by his new employer, SOHIO (eventually, British Petroleum).




A
B

